Probing gluons with exclusive production in UPCs at the LHC

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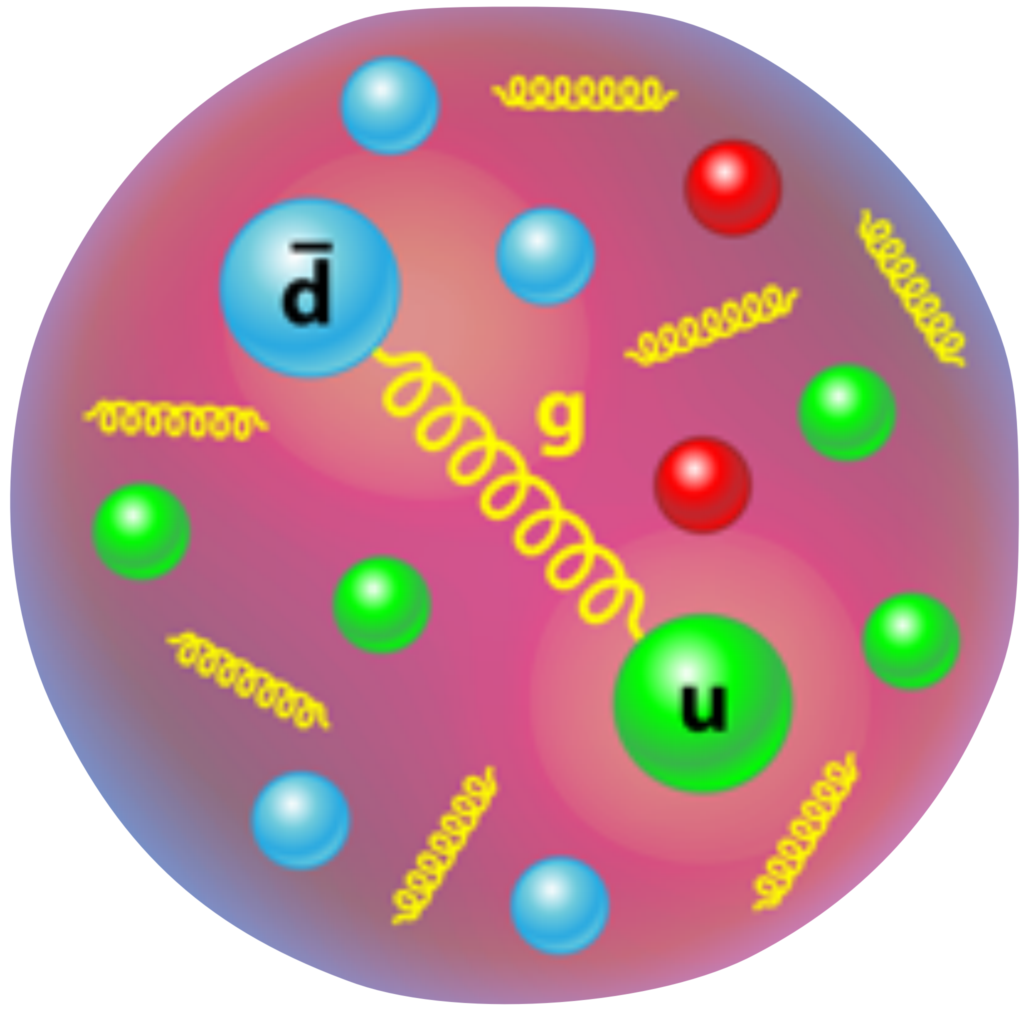
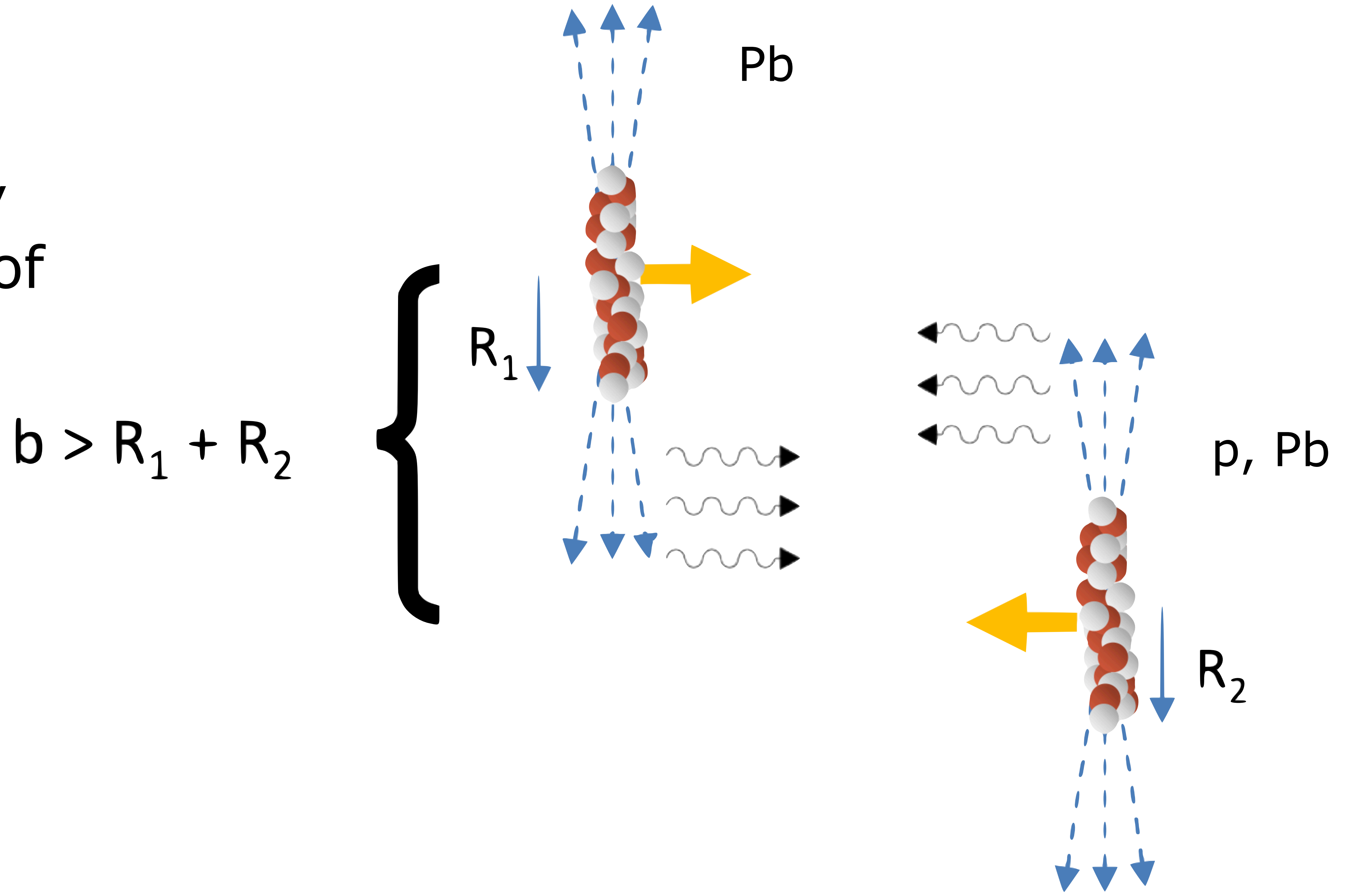


What is a UPC = Ultra Peripheral Collision?

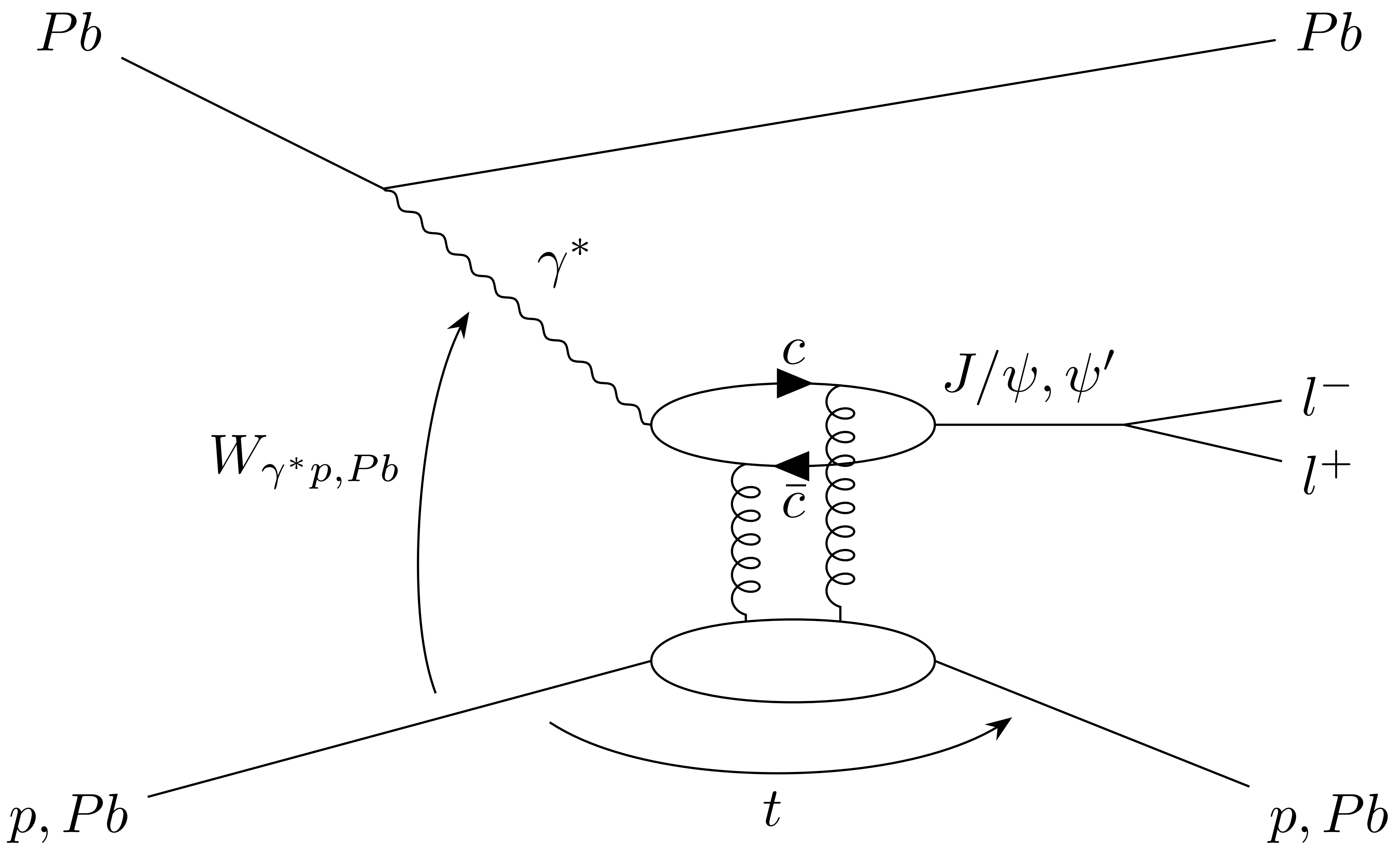
- Ultrarelativistic system
- Large impact parameter ($b > R_1 + R_2$)
- No nuclear overlap
- Reactions induced by photons with typically very small virtualities, of the order of tens of MeV^2, dominate



- Photon flux intensity $\propto Z^2$

Coherent J/ψ photoproduction in UPCs

- The virtual photon fluctuates in a $q\bar{q}$ dipole
- The virtual photon interacts with the target (p, Pb) and probes its internal structure via the exchange of 2 gluons
- From this interaction a vector meson (J/ψ, ψ') is produced (LO picture)
- Clear experimental signature of UPCs: the decay products of the vector meson are the only particles detected in an otherwise empty detector
- $Q^2 \sim m_V^2/4 \rightarrow$ the mass of the charm quark provides an energy scale large enough to allow for perturbative QCD calculations

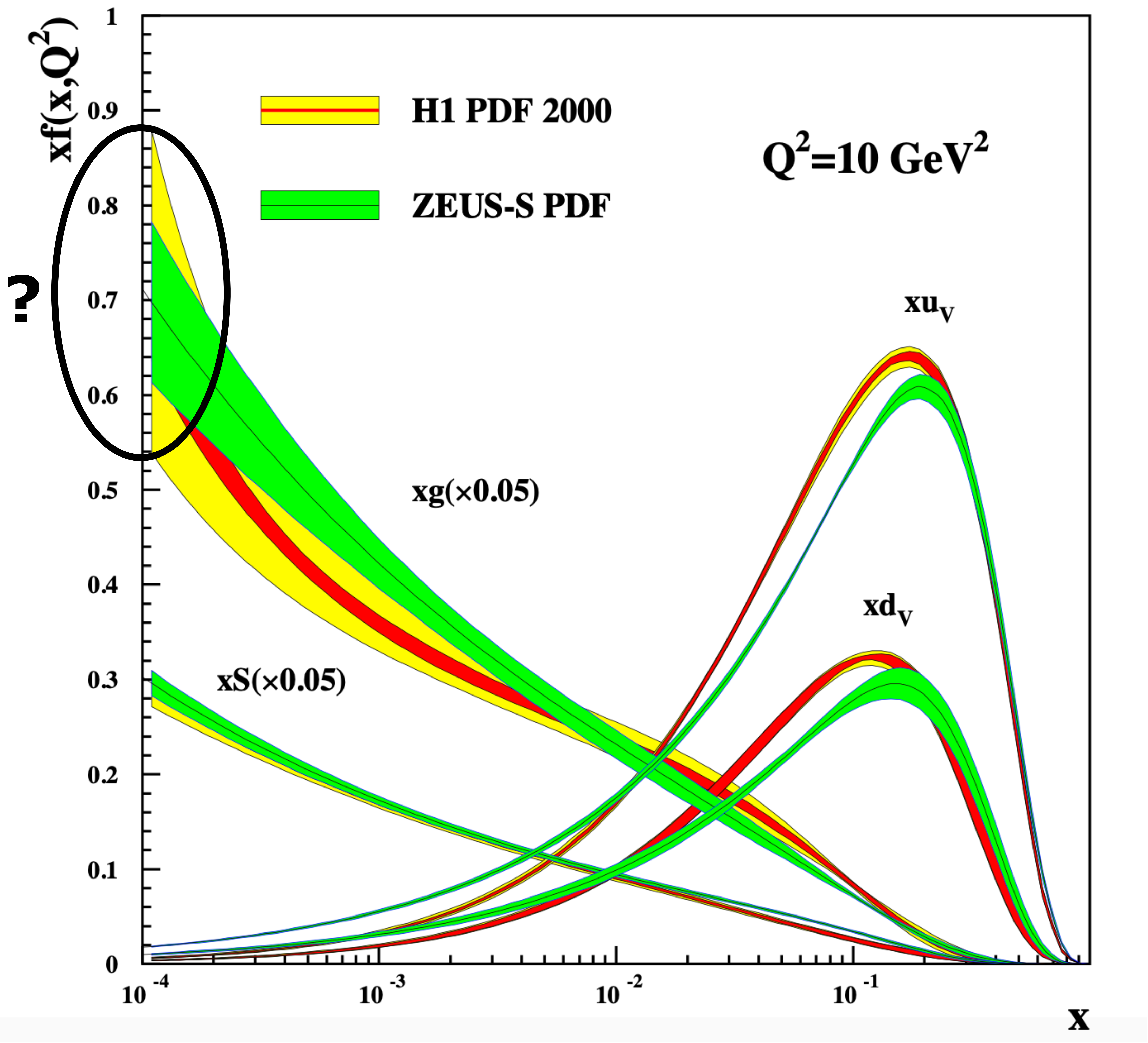


- In the case of Pb-Pb collisions, coherent interaction with the photon: the photon interacts consistently with all nucleons in a nucleus
- UPCs are of great interest to probe the target (p or Pb nuclei) and hence search for phenomena at low Bjorken-x (*shadowing, saturation...*)

Part 1: gluon saturation in p-Pb UPCs

Gluon saturation and p-Pb UPCs

- Saturation: a dynamic equilibrium between gluon radiation and recombination
- Black disk limit: area where the number of gluons stops increasing, fluctuations of the proton configurations are suppressed
- The exclusive photoproduction of charmonium off protons (γ p → J/ψ p) is a very clean probe with which to search for saturation effects, since σ(γ p → J/ψ p) ∝ [gluon density in the proton]^2 at LO in pQCD

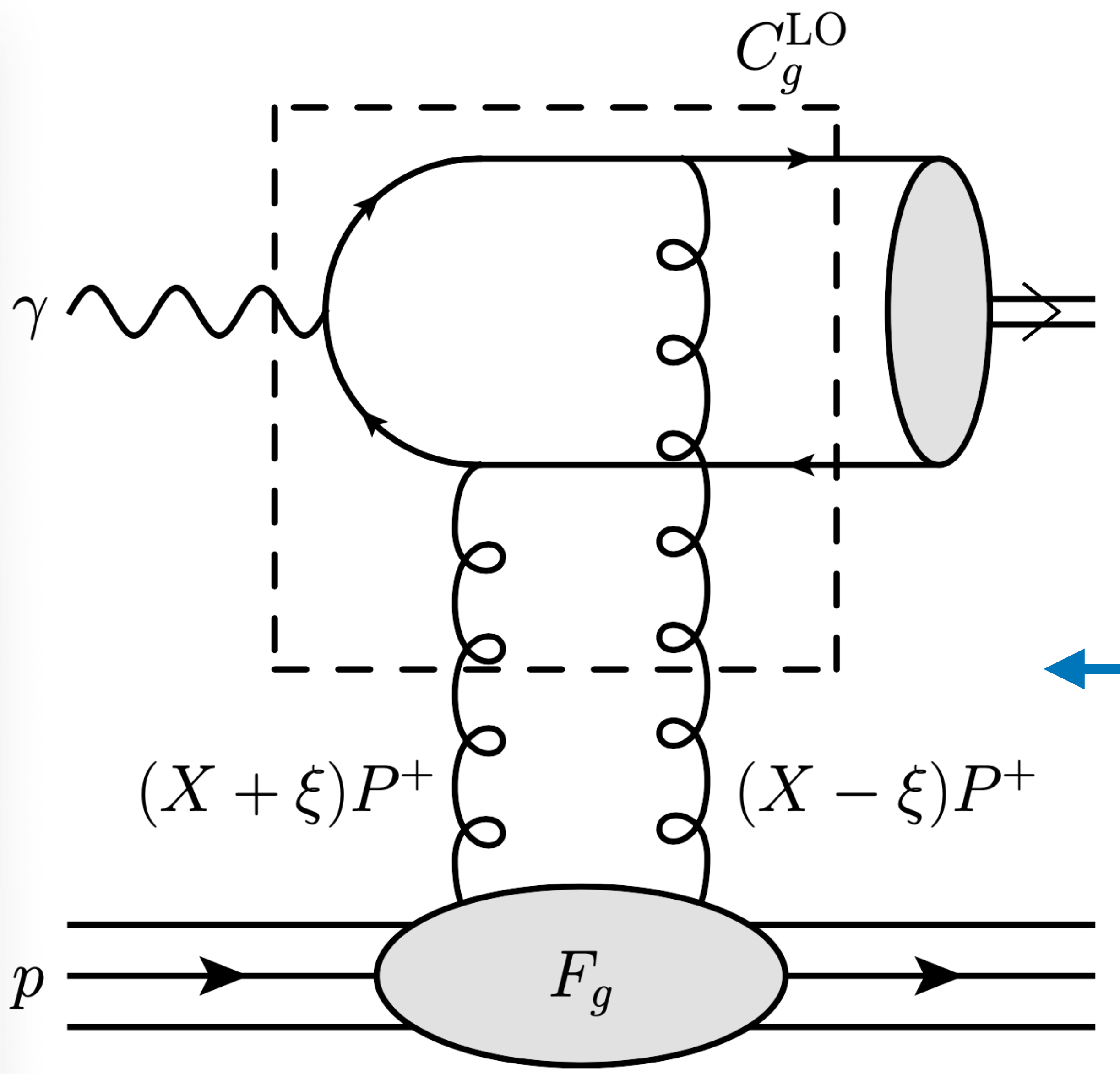


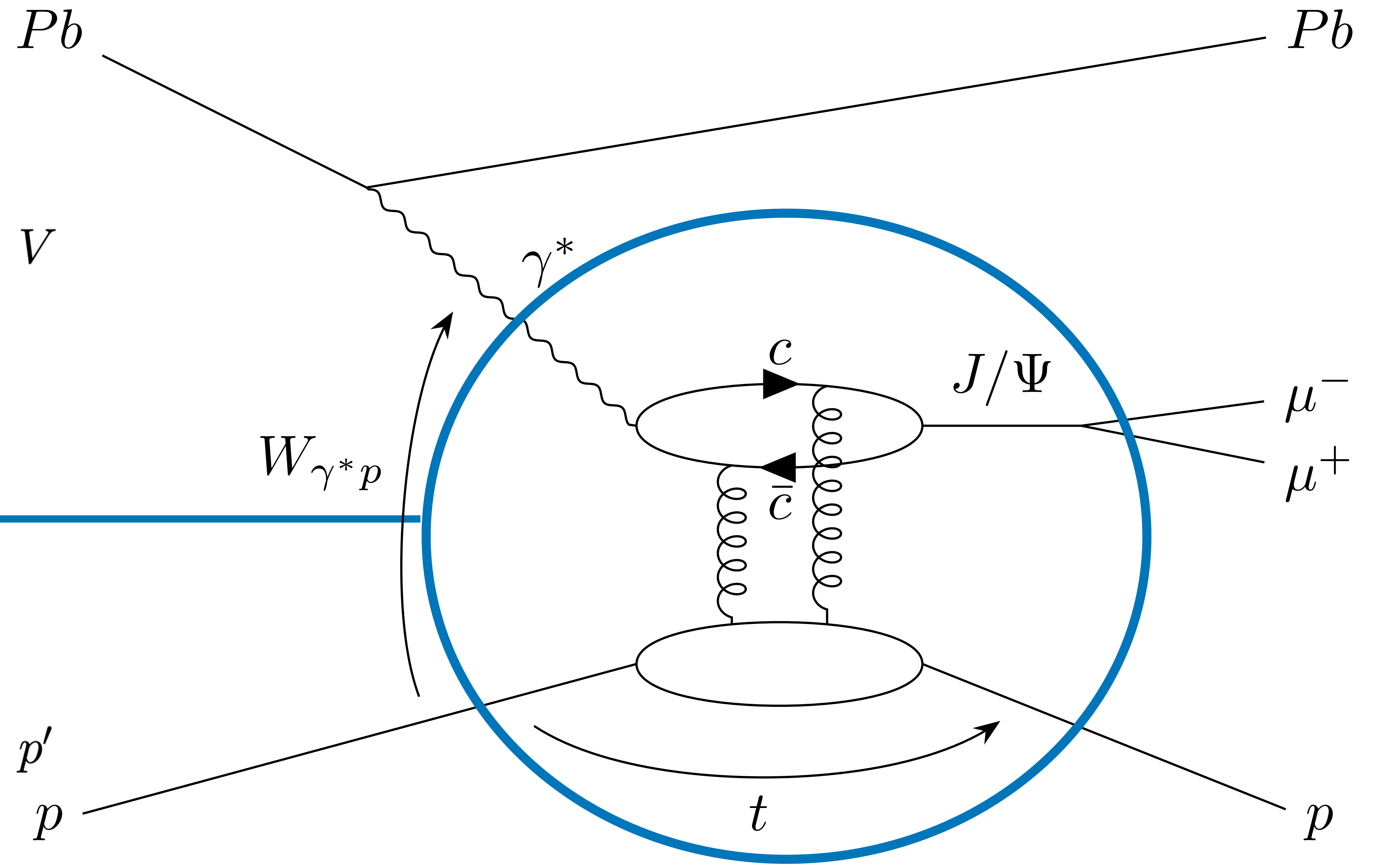
ref: L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rept. 100 (1983) 1.

Exclusive J/ψ photoproduction in p-Pb UPCs

- In fact, the non-perturbative object in the cross section is a generalised parton distribution function (GPD)
- At LO, the GPD function $F_g(X,\xi)$ accounts for the fact that the momenta of the 'left' and 'right' partons carry different proton momentum fractions X + ξ and X − ξ respectively.

(from Phys.Rev.D 101 (2020) 9, 094011)





- The Shuvaev transform: as ξ → 0 (and at t = 0),

GPD $F_g(X, \xi)$ → PDF(x = X + ξ)

relevant values of X in the convolution of the GPD with the coefficient function are of the order of ξ

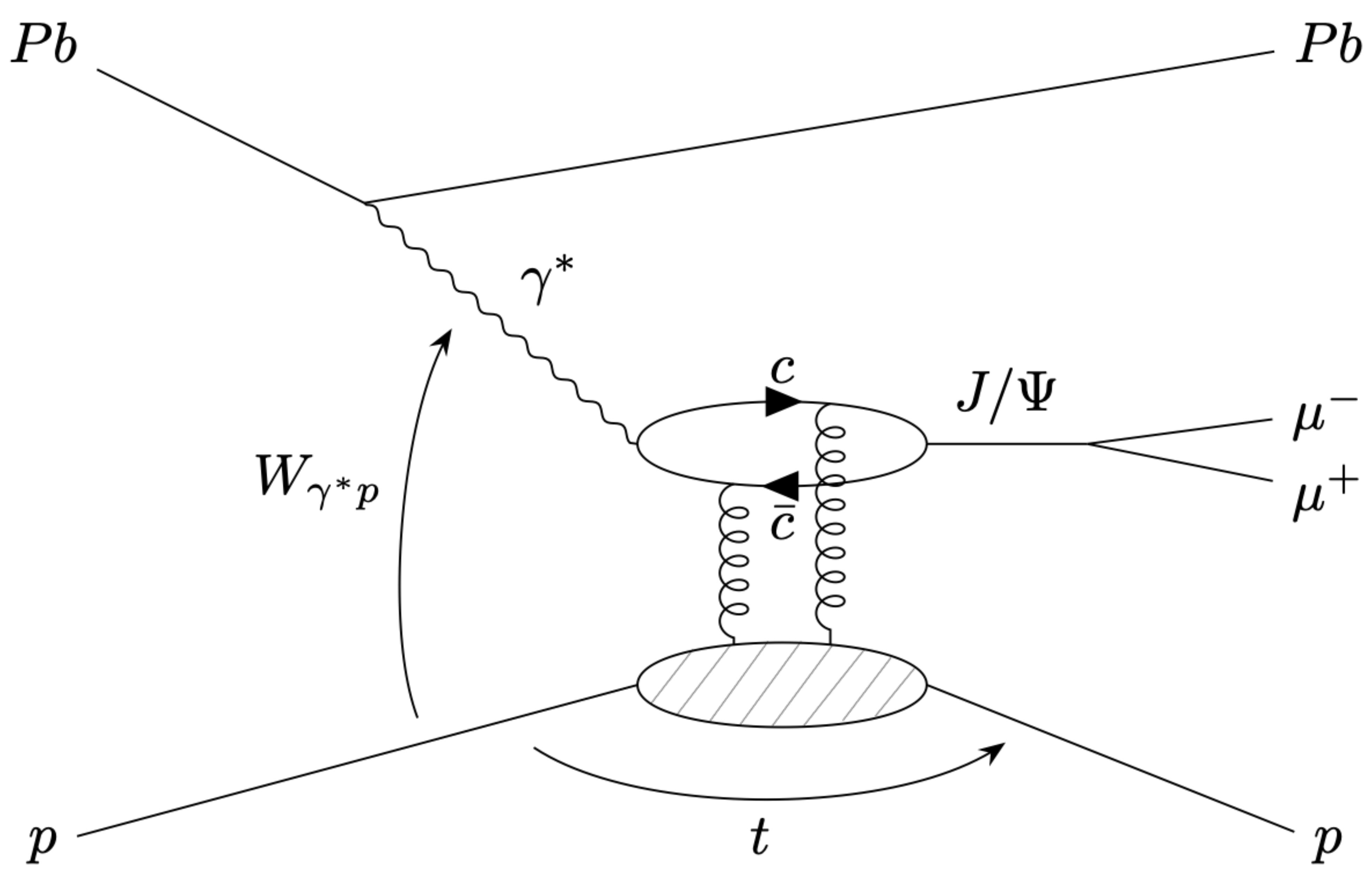
→ gluon PDF is probed for $x \sim 2\xi$

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\Psi\ p)\bigg|_{t=0} \propto [xg(x, Q^2)]^2$$

Exclusive J/ψ photoproduction in p-Pb collisions

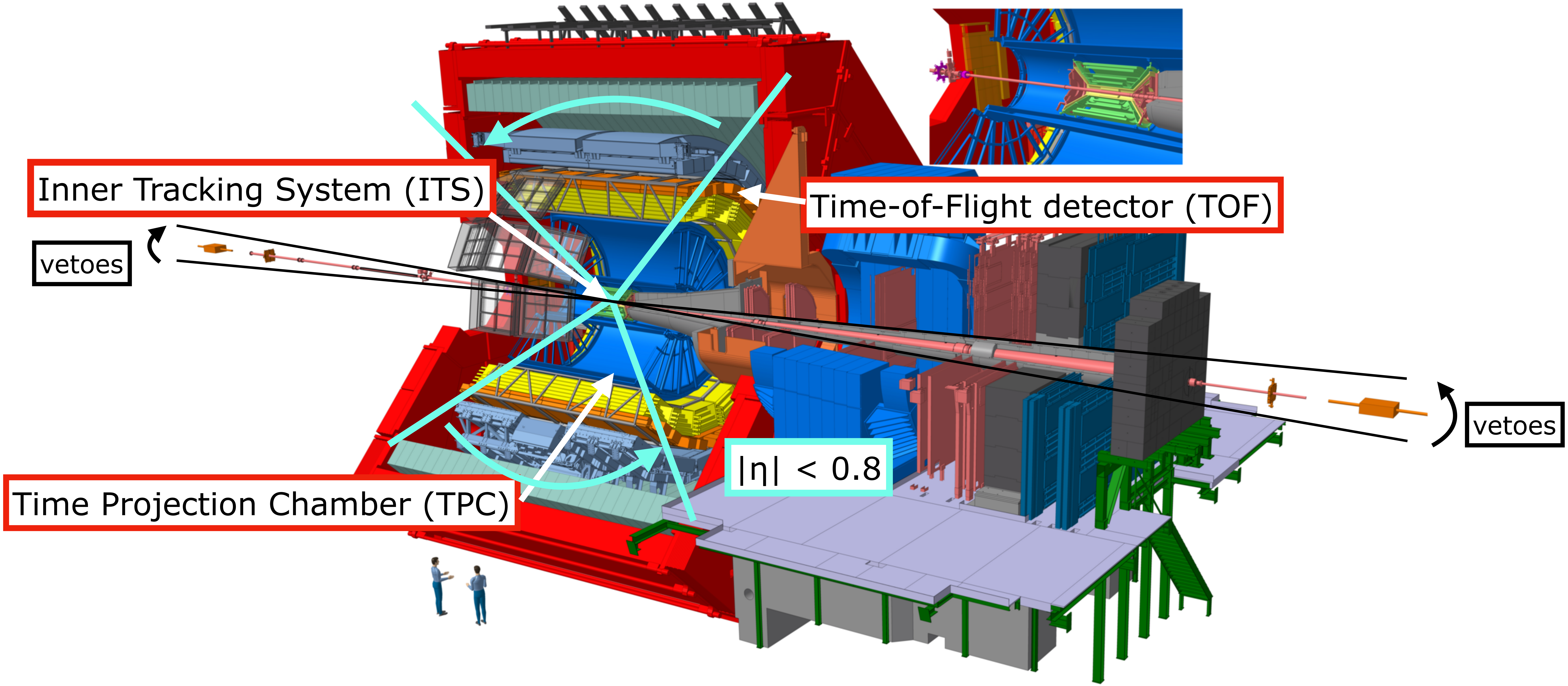
- Pb nucleus is the γ-emitter in 95% of the cases
- Center-of-mass energy per nulceon $\sqrt{s_{NN}}$ = 5.02 TeV
- Measurements performed in
  - the mid (|y| < 0.8),
  - semi-backward (−2.5 < y < −1.2),
  - semi-forward (1.2 < y < 2.7),
  - backward (−3.6 < y < −2.6),
  - and forward (2.5 < y < 4)

rapidity intervals

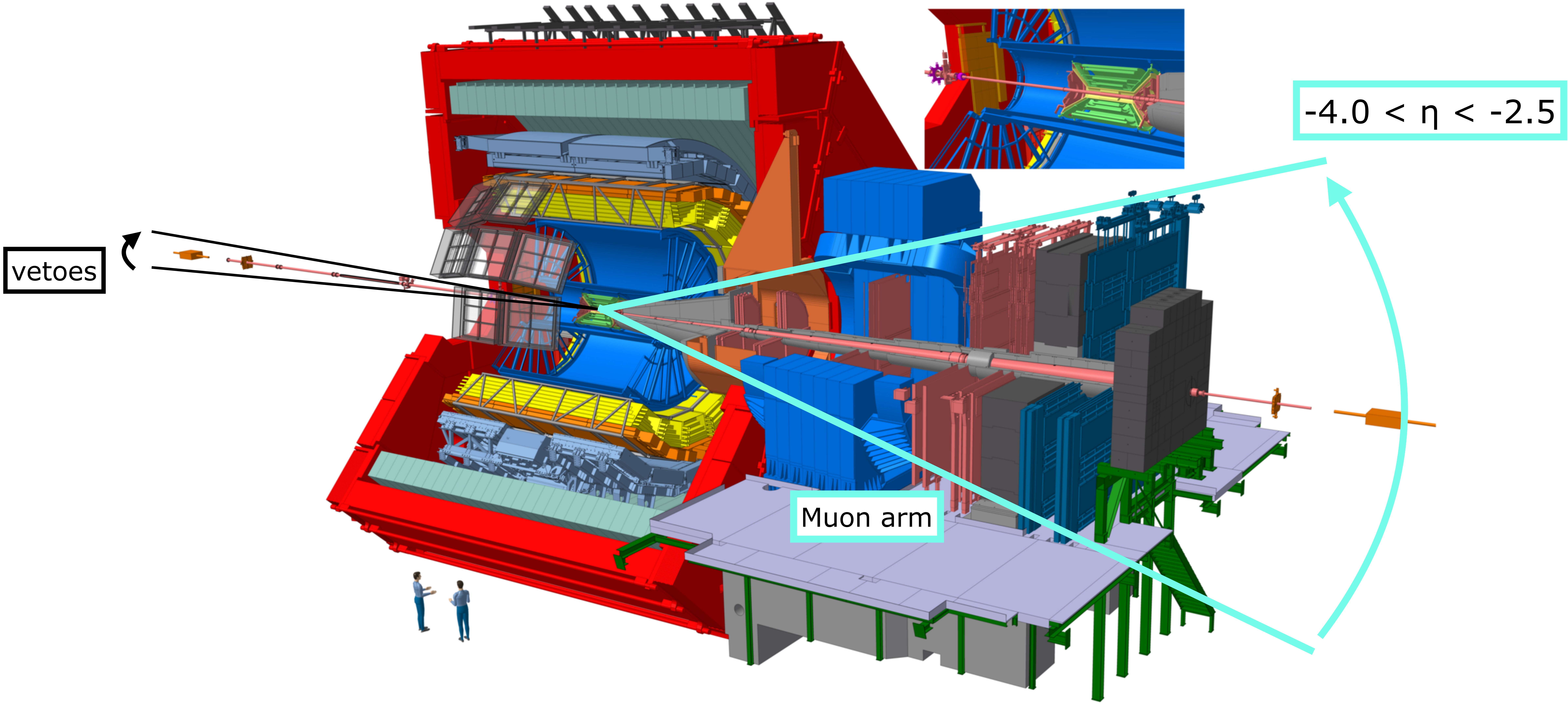


- p-γ* center-of-mass energy given by $W^2_{\gamma^* p} = 2E_p\, M_{J/\Psi}\, e^{-y}$ where y is the rapidity of the J/ψ defined according to the proton beam
- Thus, measurements in ALICE in Run 1 span the $W_{\gamma p}$ range from 20 to 700 GeV

Selection of data (mid-rapidity)

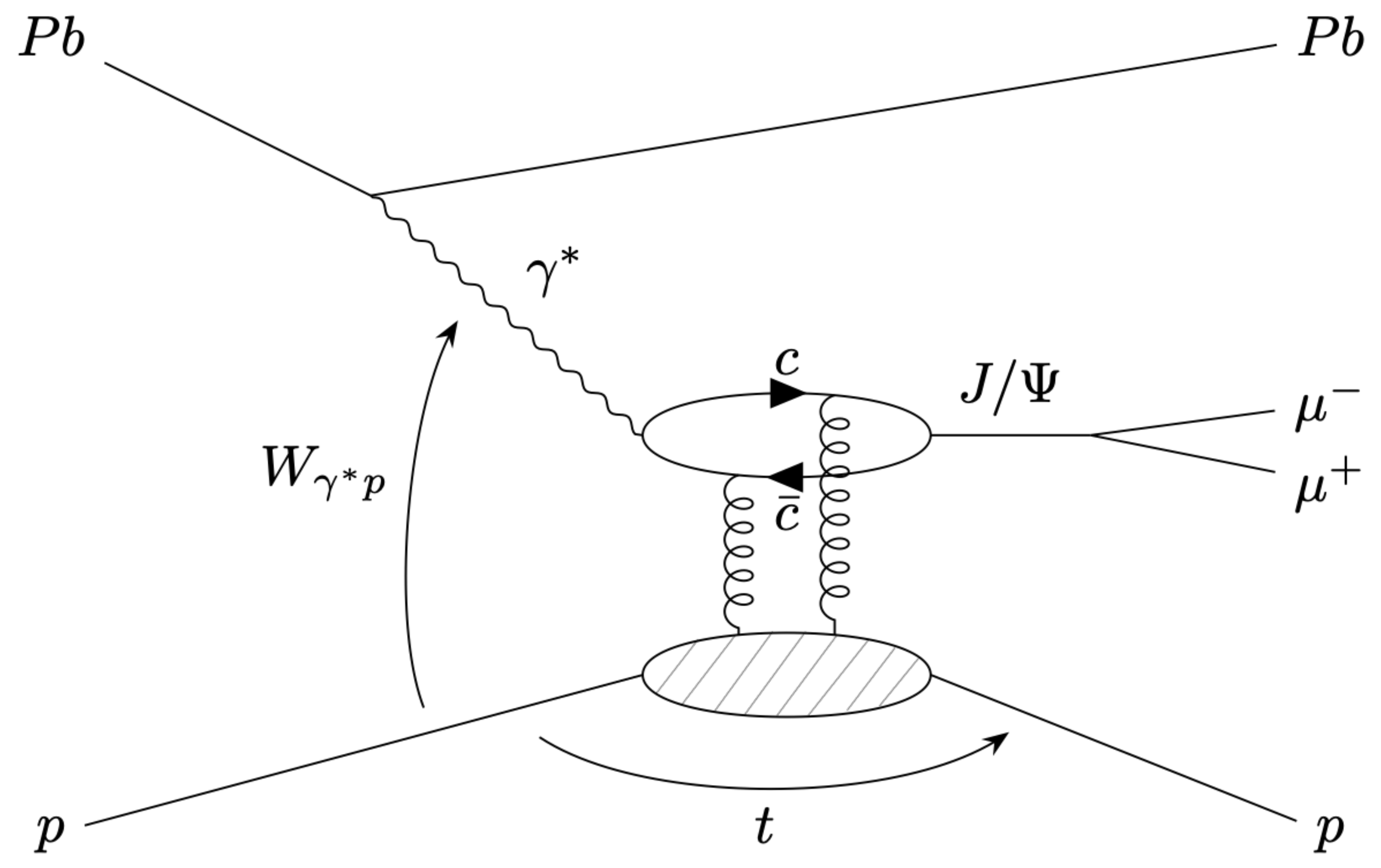


Selection of data (forward rapidity)

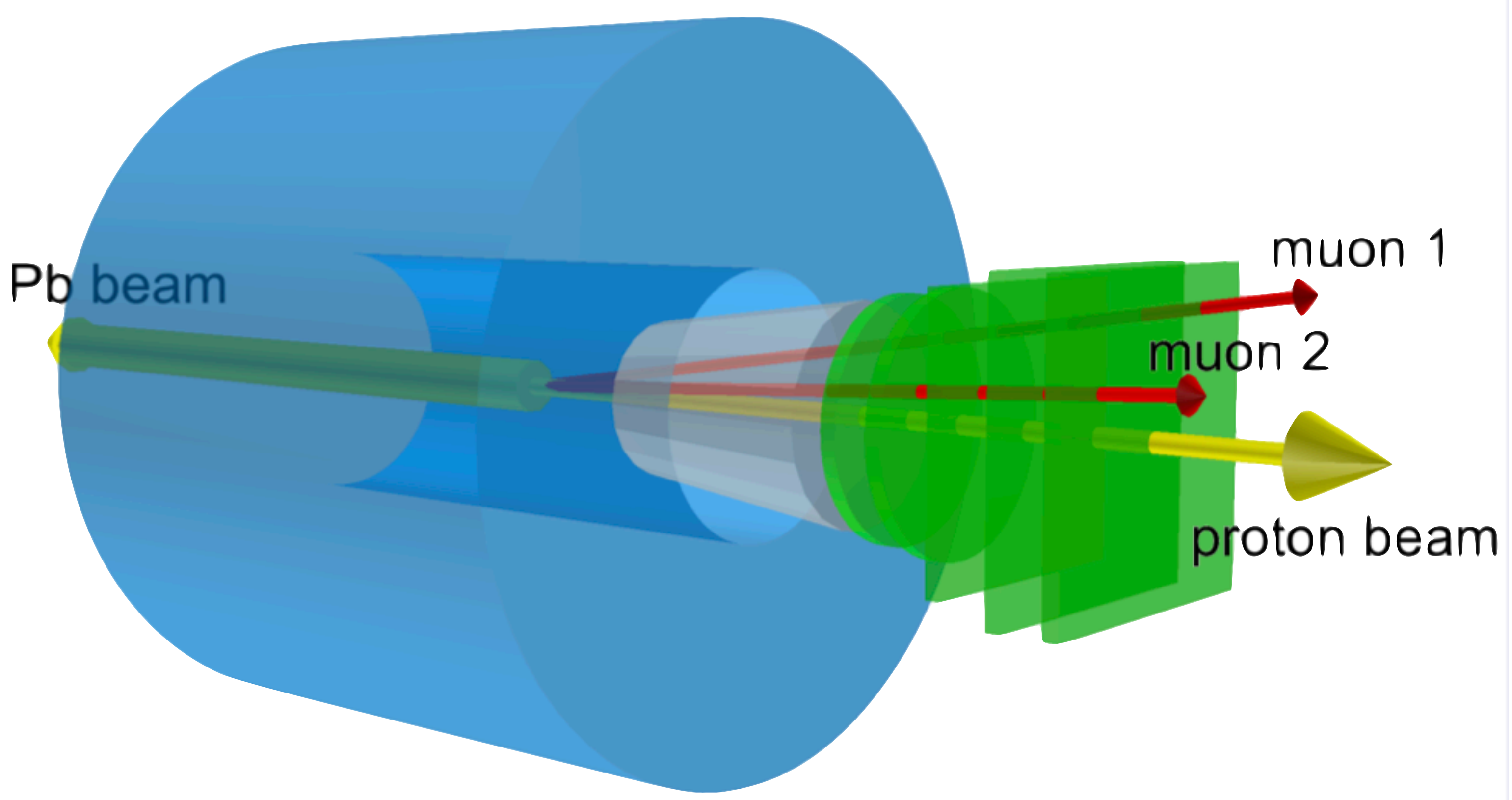


J/ψ photoproduction in p-Pb collisions at forward rapidity

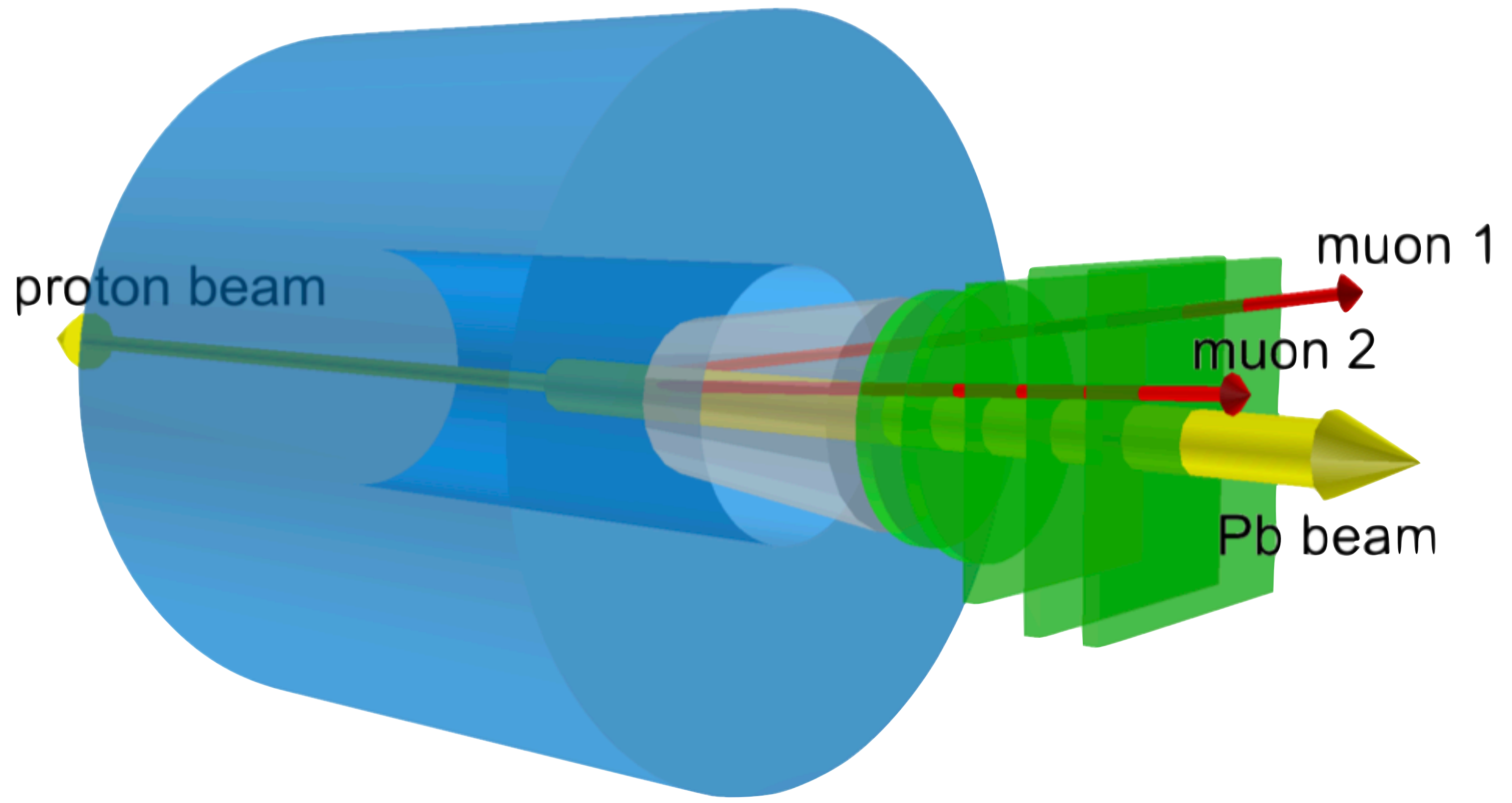
- Pb nucleus is the γ-emitter in 95% of the cases
- p-γ* center-of-mass energy given by $W^2_{\gamma^* p} = 2E_p\, M_{J/\Psi}\, e^{-y}$ where y is the rapidity of the J/ψ defined according to the proton beam
- Bjorken-x: $x \propto W^{-2}_{\gamma^* p}$
- 2 most extreme energy configurations obtained from the muon arm:



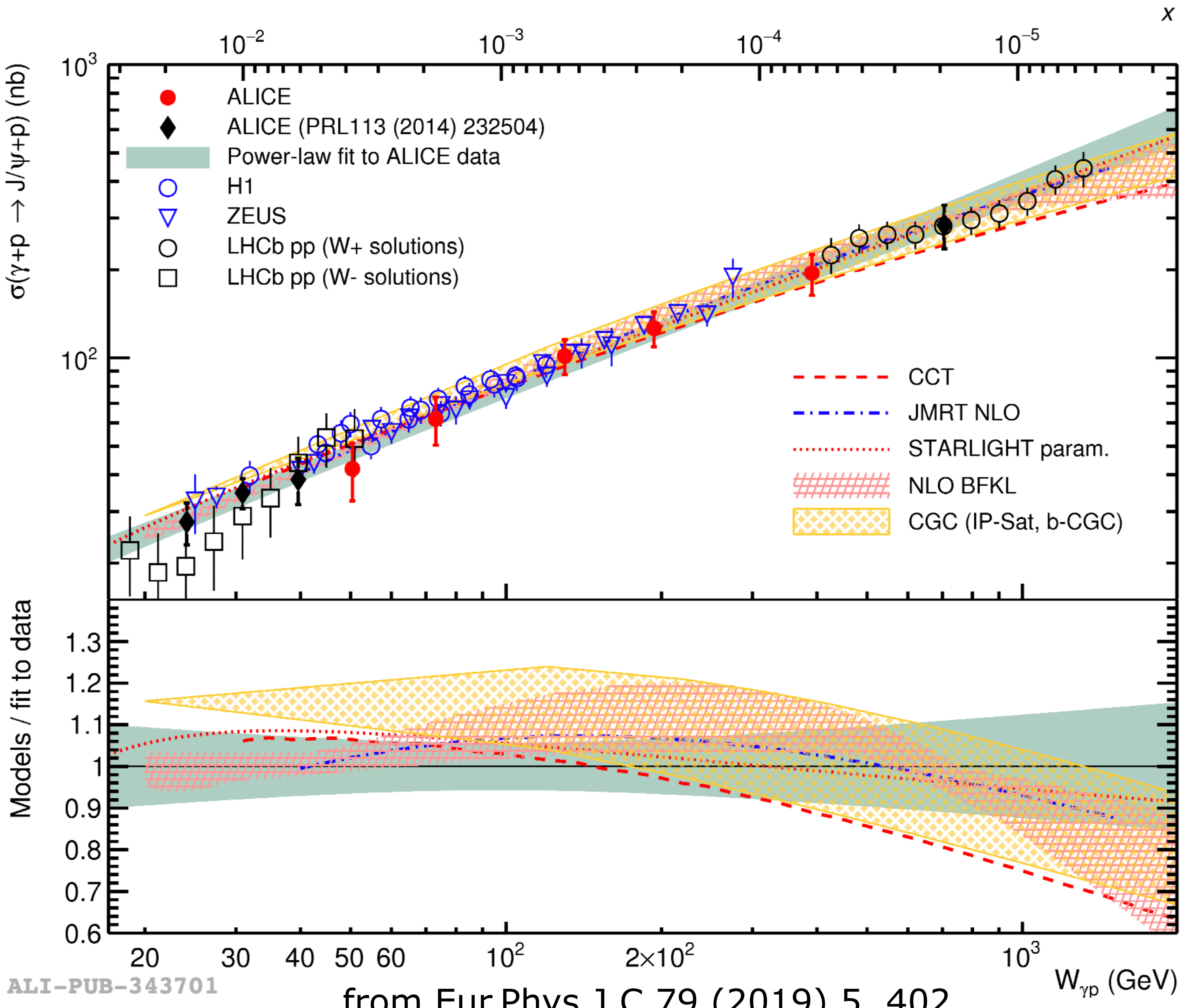
the J/ψ goes in the direction of the proton:
21 GeV < $W_{\gamma^* p}$ < 45 GeV
$(2 \times 10^{-2} < x < 4 \times 10^{-2})$



the J/ψ goes in the direction of the Pb ion:
580 GeV < $W_{\gamma^* p}$ < 955 GeV
$(2 \times 10^{-5} < x < 5 \times 10^{-5})$



Looking for gluon saturation at LHC: published measurements



from Eur.Phys.J.C 79 (2019) 5, 402

- σ($W_{\gamma^* p}$) ∝ [gluon PDF of the proton]^2
- Power-law fit σ ~ $W^{\delta}_{\gamma^* p}$
- In a lowest order formulation, σ ~ $W^{\delta}_{\gamma^* p}$ → xg(x) ~ $x^{-\delta/2}$
  - a change in slope might be a sign of the onset of gluon saturation effects
- Fit to ALICE data (Run 1) alone: δ = 0.68 ± 0.06 → no deviation from a power law is observed up to about 700 GeV

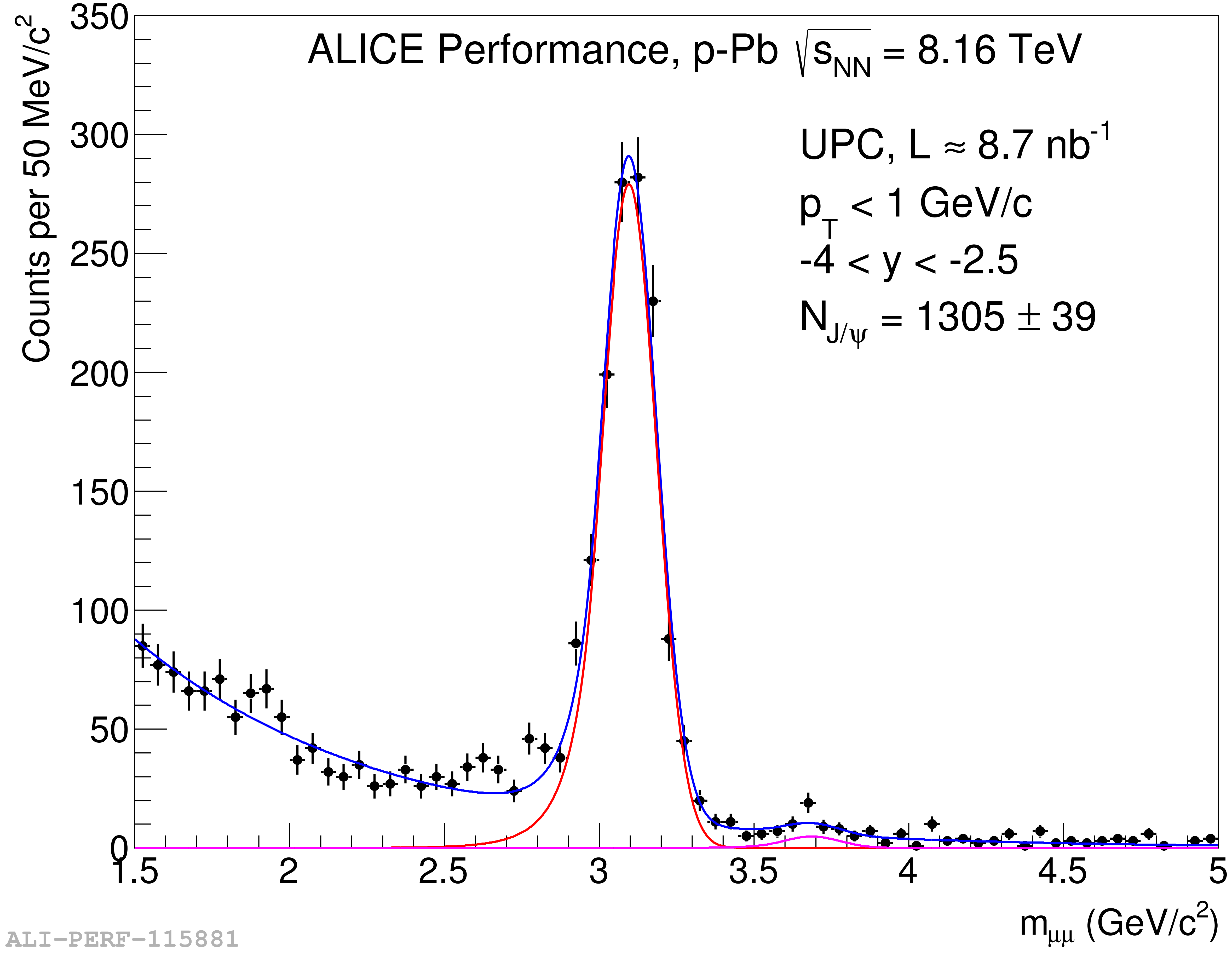
(ZEUS: δ = 0.69 ± 0.02 (stat) ± 0.03 (syst), H1: δ = 0.67 ± 0.03 (stat + syst))

- LHCb studied the same process in p-p collisions (symmetric system : low energy contribution constrained via HERA data)
- HERA: H1 and ZEUS have measured the cross section of J/ψ photoproduction at energies $W_{\gamma^* p}$ from 20 to 305 GeV

- No change in the behavior of the gluon PDF in the proton is observed between HERA and LHC energies

Run 2 data in p-Pb (2016)

Performance plot for 2016 data at forward rapidity



data	2013	2016
CM energy in the p-Pb system	5.02 TeV	8.16 TeV
Maximum $W_{\gamma^* p}$	900 GeV	1500 GeV
Luminosity	3.9 nb^{-1} in p-Pb (4.5 nb^{-1} in Pb-p)	7.6 nb^{-1} in p-Pb (11.9 nb^{-1} in Pb-p)
Kinematic regime at forward rapidity (min x)	$x \sim 2 \times 10^{-4}$	$x \sim 4 \times 10^{-6}$

- Ongoing analysis with the first measurement of dissociative J/ψ where the target proton breaks up

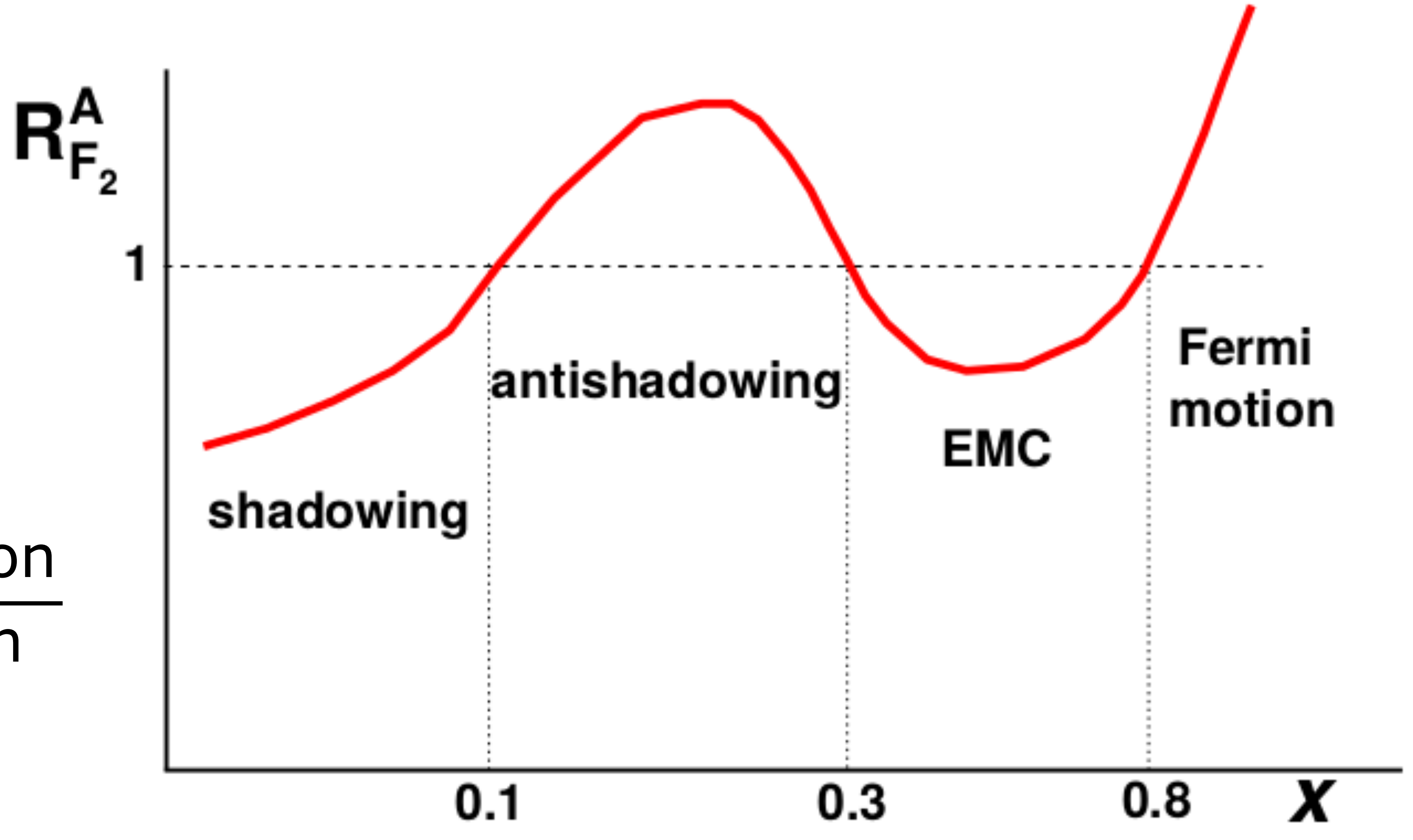
Part 2: gluon shadowing in Pb-Pb UPCs

What is shadowing?

- Nuclear structure functions in nuclei are different from the superposition of those of their constituent nucleons
- The nuclear ratio is defined as the nuclear structure function per nucleon divided by the nucleon structure function

$$R^A_{F_2}(x,Q^2) = \frac{F_2^A(x,Q^2)}{AF_2^{nucleon}(x,Q^2)}$$

- Gluon shadowing factor $R_g(x,Q^2) = \frac{\text{nuclear gluon density distribution}}{\text{gluon distribution in the proton}}$
- At LO pQCD, $\frac{d\sigma^{coh}}{dt}(\gamma^* p, \mathrm{Pb} \rightarrow J/\Psi\ p, \mathrm{Pb})\Big|_{t=0} \propto$ [gluon density]^2 [1]
- Hence $R_g(x,Q^2) \approx \sqrt{\frac{\sigma^{coh}(\gamma + \mathrm{Pb} \rightarrow J/\psi + \mathrm{Pb})}{\sigma^{IA}(\gamma + \mathrm{Pb} \rightarrow J/\psi + \mathrm{Pb})}}$ where $\sigma^{IA}(\gamma + \mathrm{Pb} \rightarrow J/\psi + \mathrm{Pb})$ is the photoproduction cross section in the impulse approximation based on the exclusive photoproduction measurements with the proton target
- Can be studied in ultra-peripheral collisions of Pb-Pb nuclei at the LHC via the study of coherent J/ψ photoproduction off lead nuclei (γ + Pb → J/ψ + Pb)



J.Phys.G 32 (2006) R367-R394

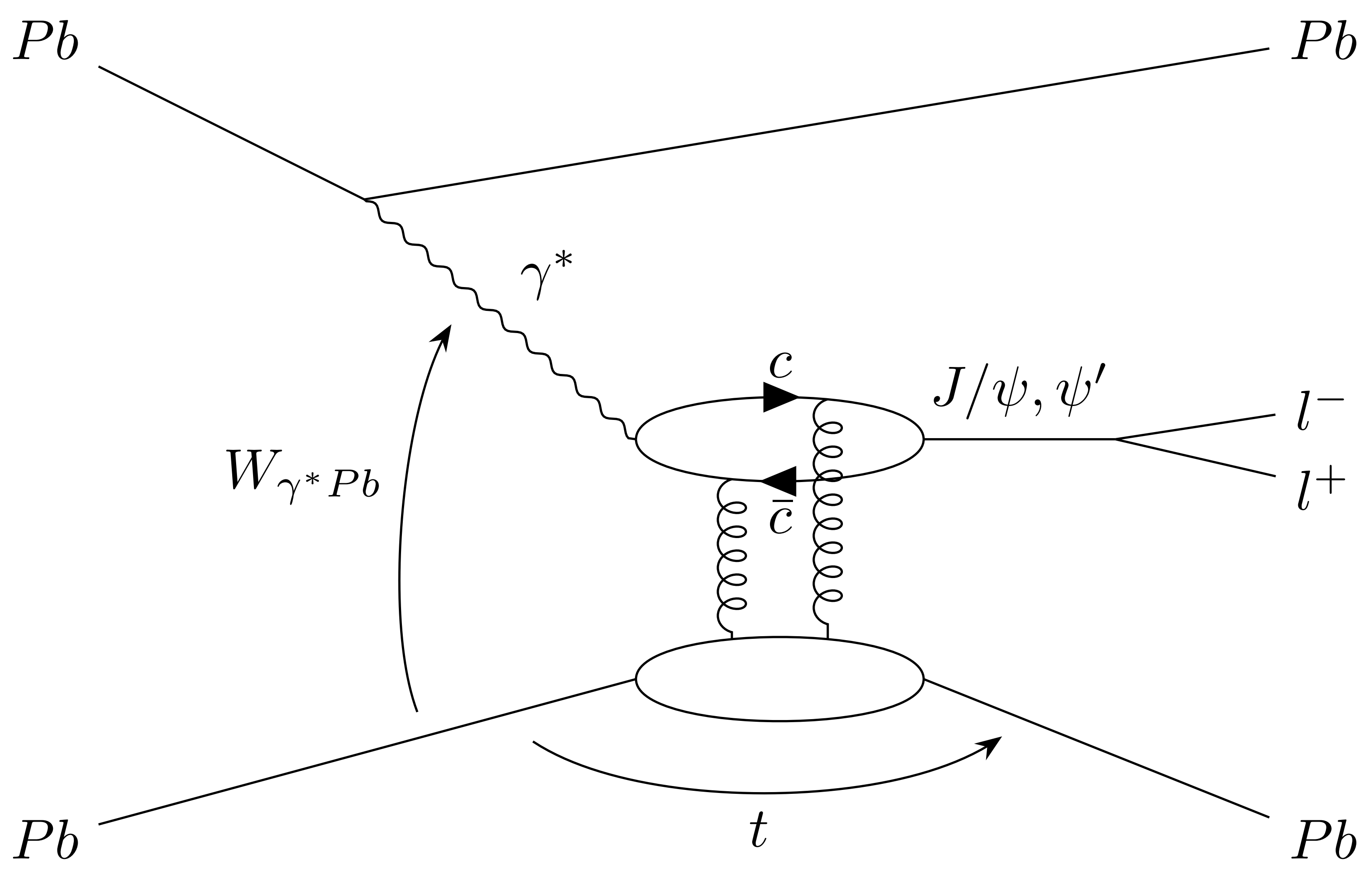
[1] https://doi.org/10.1007/BF01555742

Pb-Pb collisions in ALICE

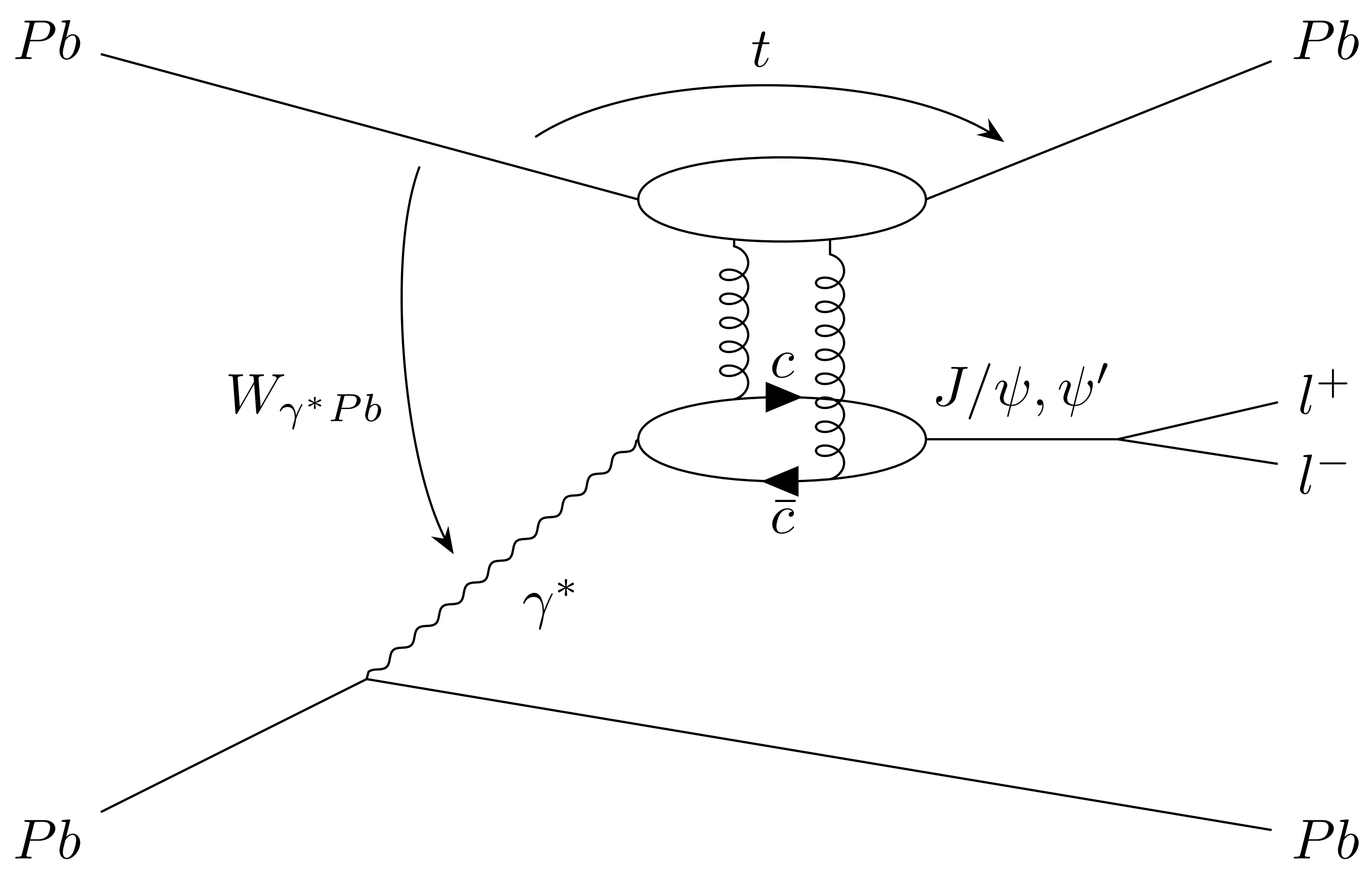
In the limit t → 0, the Bjorken-x variable can be defined as:

$$x = \frac{m_V}{\sqrt{s_{NN}}} \exp(\pm y)$$

where m_V is the mass of the coherently produced $c\bar{c}$ states and y its rapidity



$$x = \frac{m_V}{\sqrt{s_{NN}}} \exp(-y)$$



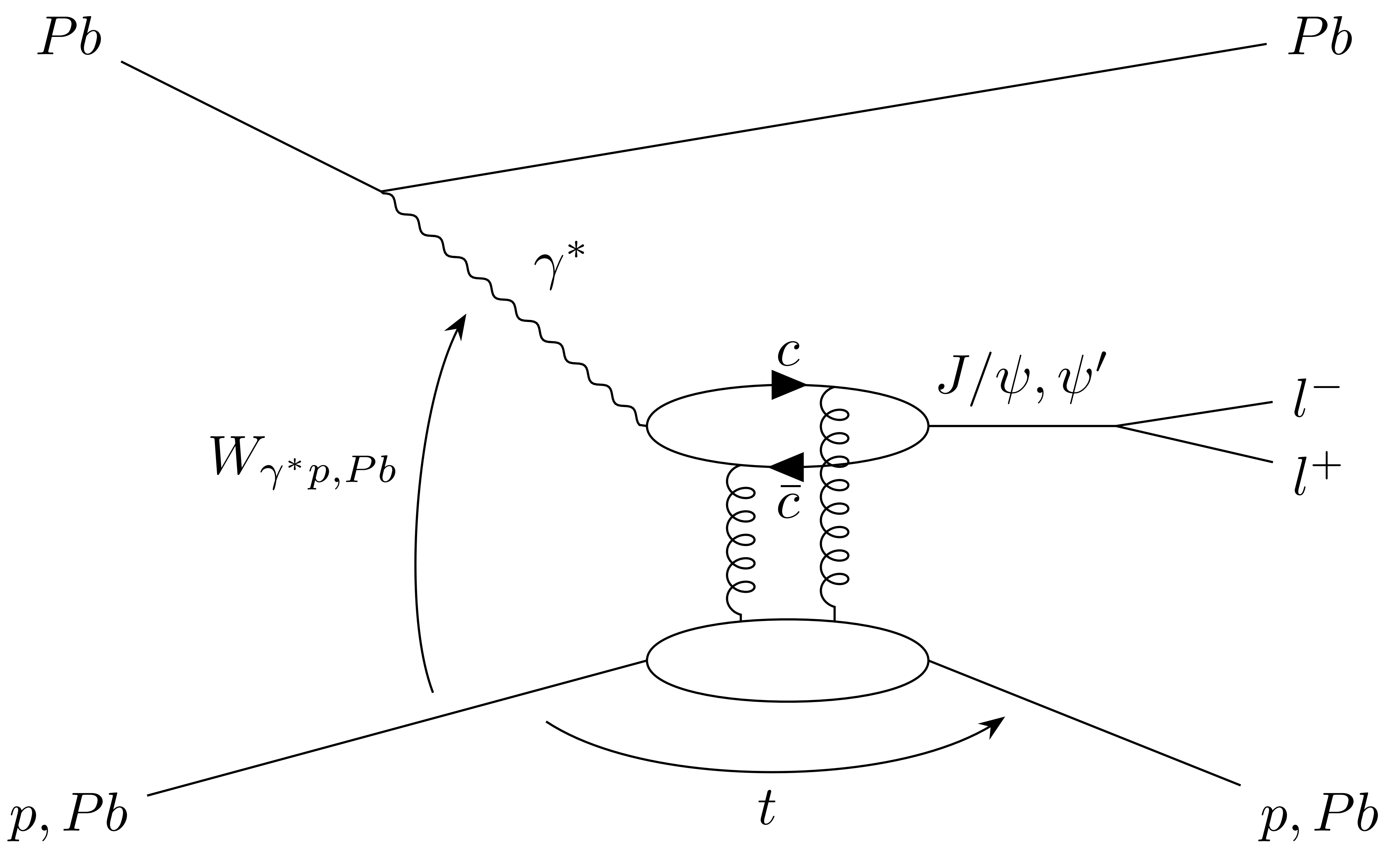
$$x = \frac{m_V}{\sqrt{s_{NN}}} \exp(+y)$$

→ Low Bjorken-x values ranging from $x \sim 10^{-5}$ to $x \sim 10^{-2}$ at LHC energies

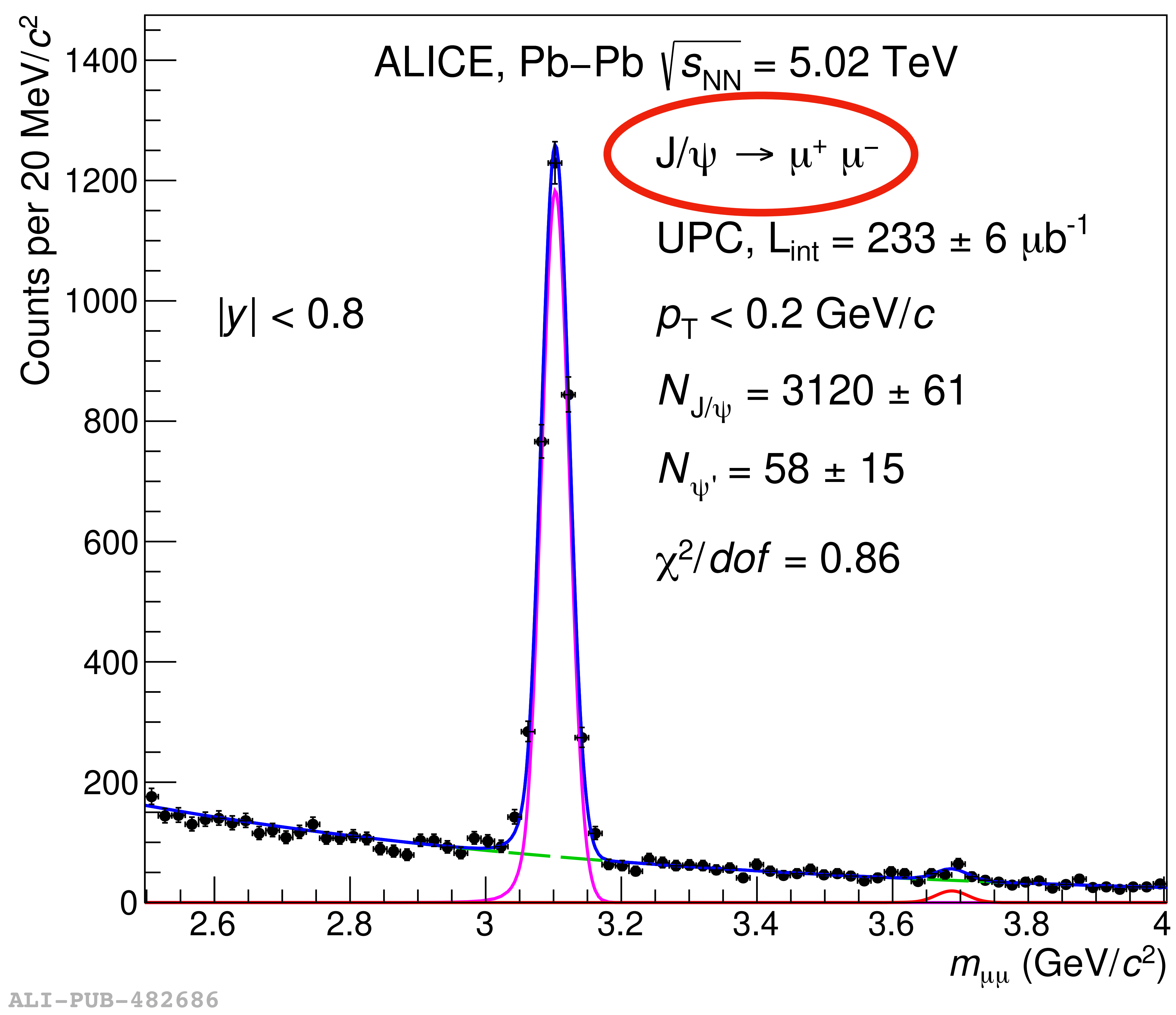
J/ψ and ψ' photoproduction in UPCs

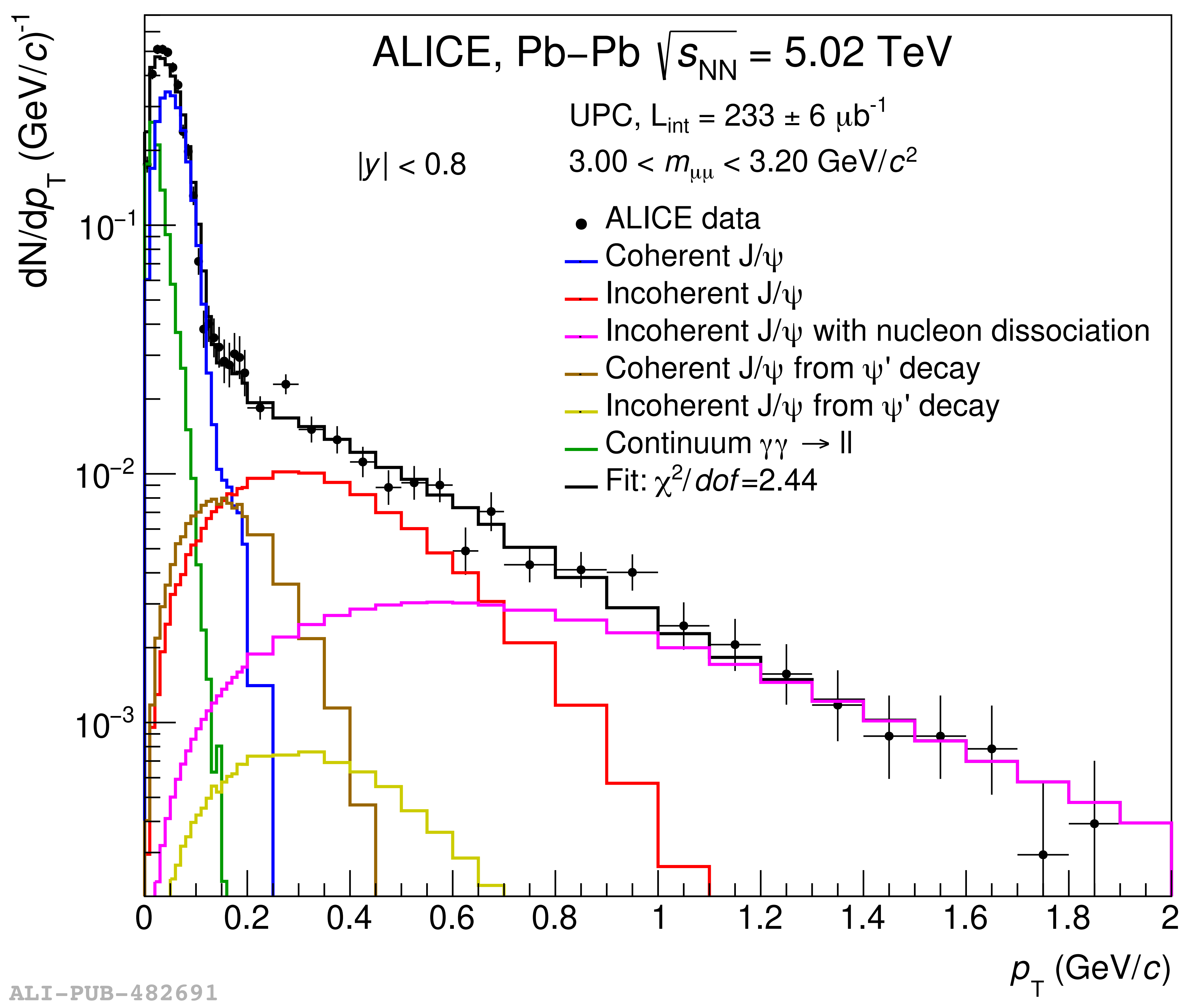
Measurements performed:

- At forward rapidity ($-4.0 < y < -2.5$): study of $J/\psi \rightarrow \mu^+\mu^-$
- At mid-rapidity ($|y| < 0.8$ in Run 2): study of
  - $J/\psi \rightarrow \mu^+\mu^-$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow p\bar{p}$
  - $\psi' \rightarrow l^+l^-$, $\psi' \rightarrow J/\psi\ \pi^+\pi^-$ followed by $J/\psi \rightarrow l^+l^-$



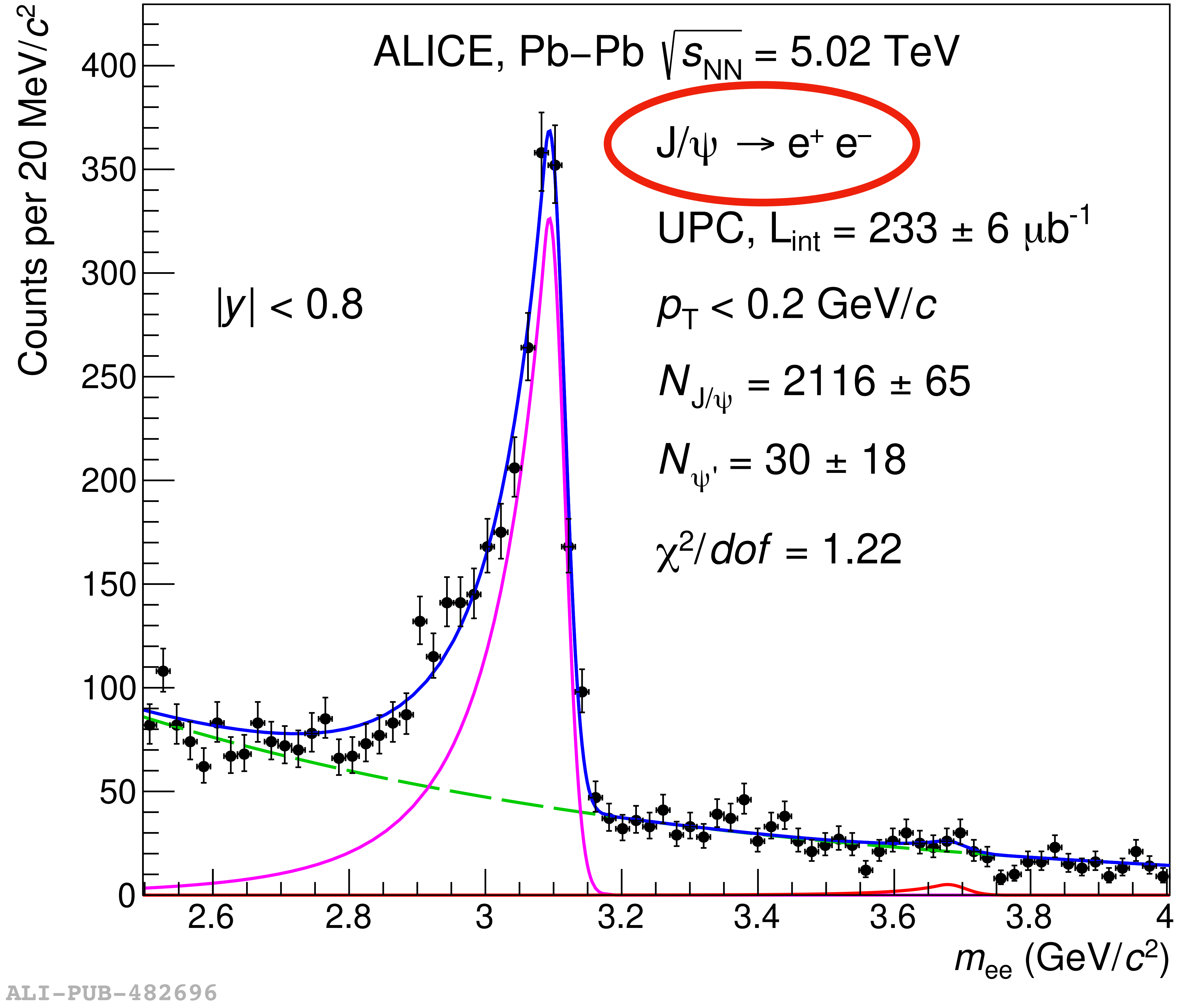
Signal reconstruction at mid-rapidity

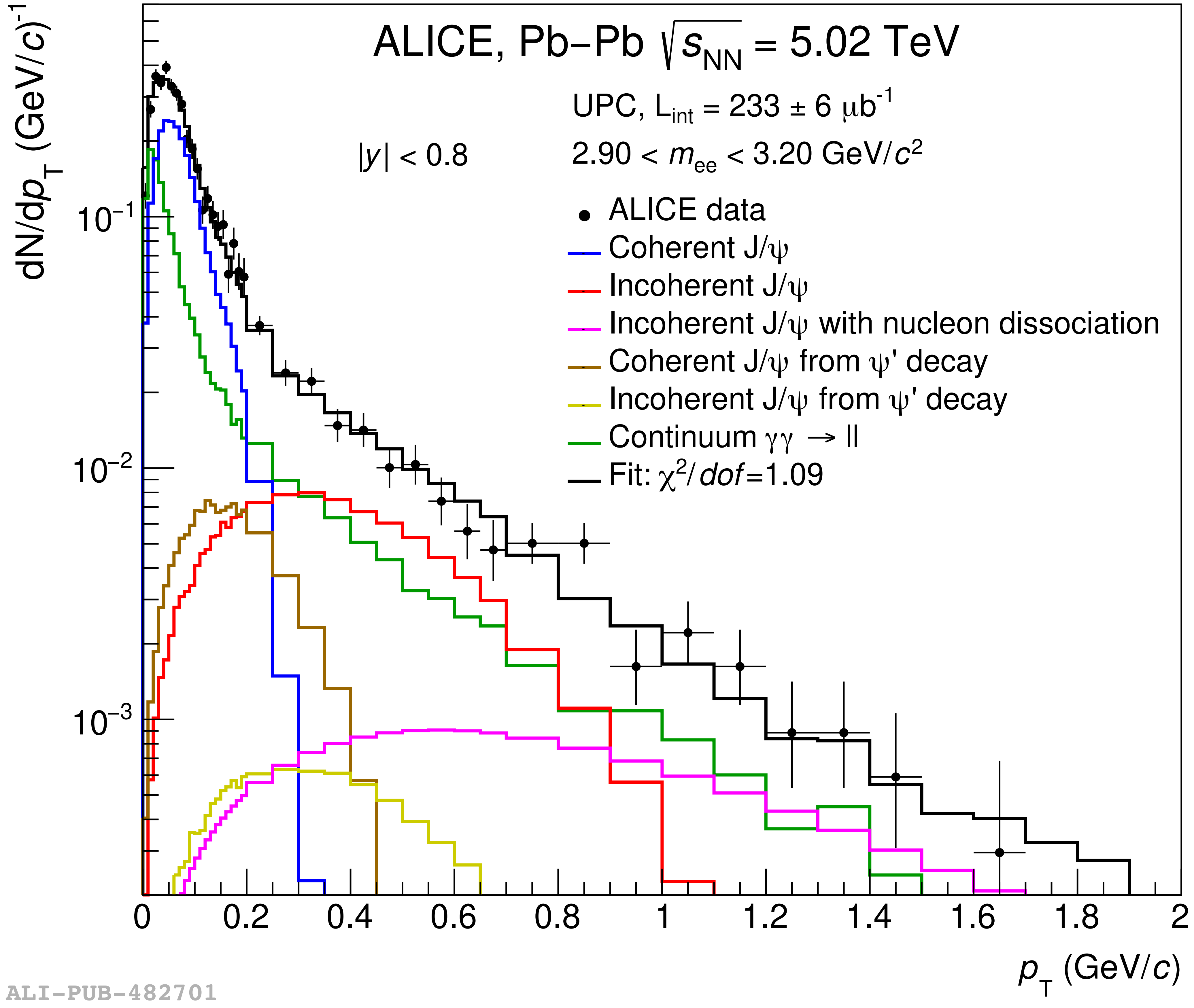




from ALICE collaboration, arXiv:2101.04577 [nucl-ex]]

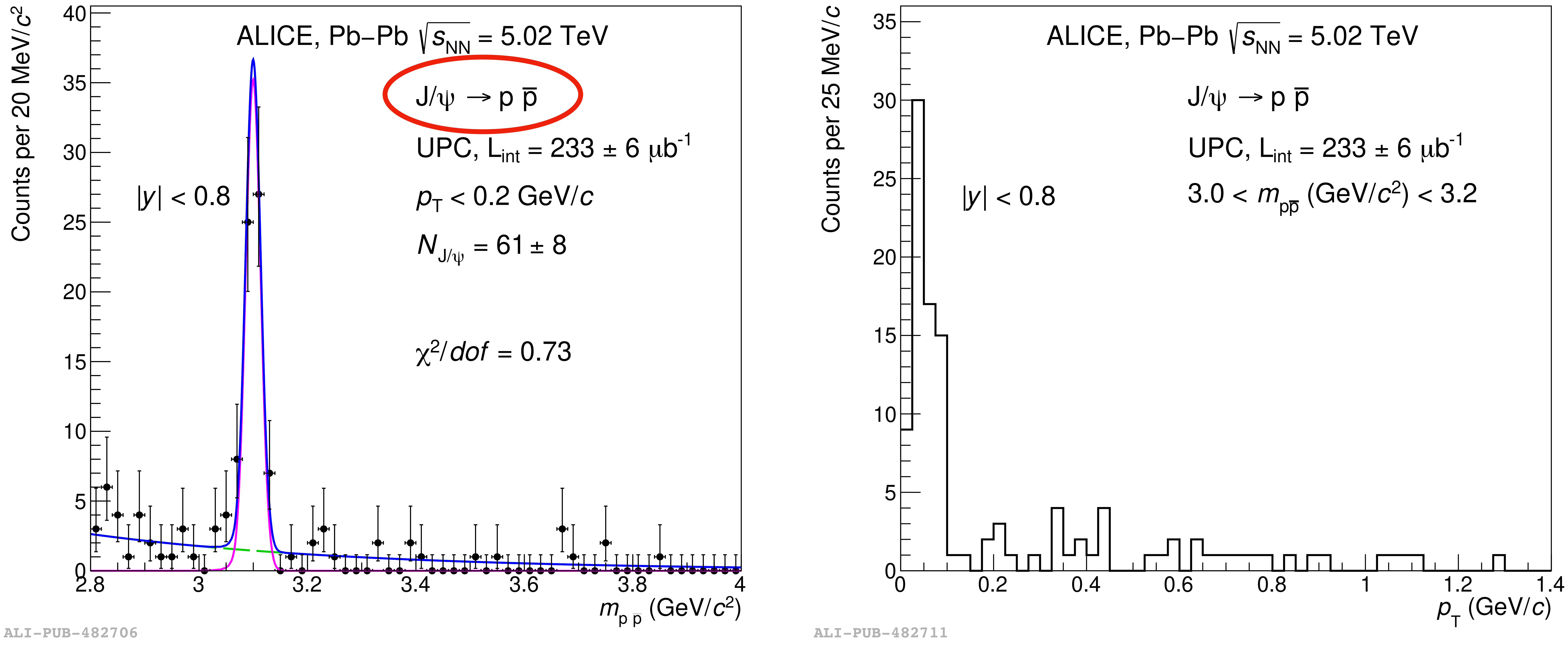
Signal reconstruction at mid-rapidity





from ALICE collaboration, arXiv:2101.04577 [nucl-ex]]

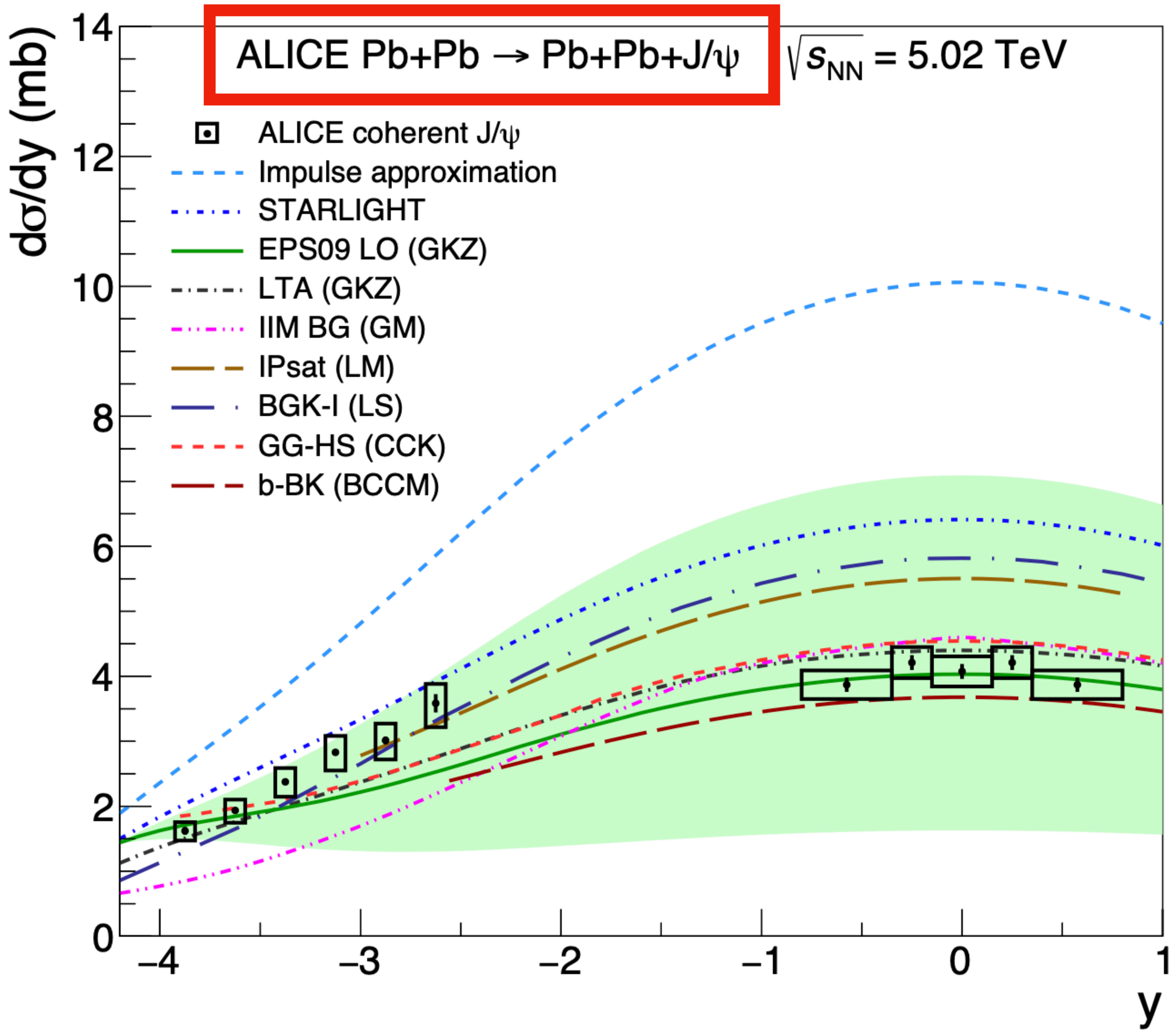
Signal reconstruction at mid-rapidity

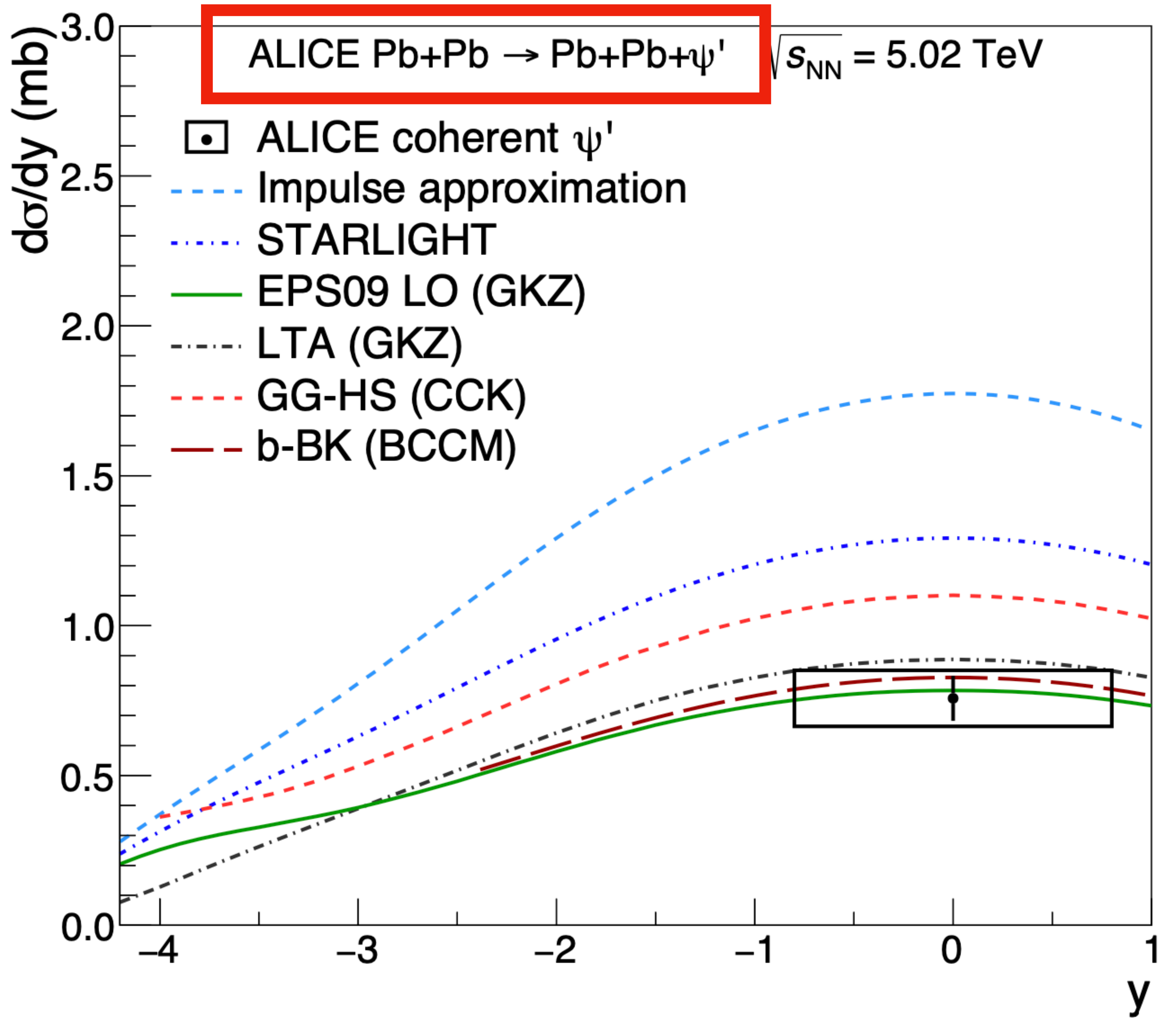


from ALICE collaboration, arXiv:2101.04577 [nucl-ex]]

Measurement of dσ/dy and comparison with the models

- Mid-rapidity:
  - L_{int} = 233 μb^{-1} (Run 1 data: integrated luminosity = 55 μb^{-1})
  - measurement of $\sigma_{J/\psi}$ in 3 rapidity intervals
  - N(J/ψ → μμ) = 3120
- Forward rapidity:
  - L_{int} = 754 μb^{-1}
  - measurement of $\sigma_{J/\psi}$ in 6 rapidity intervals
  - N(J/ψ → μμ) = 21800 and N(J/ψ → ee) = 2116





from ALICE collaboration, arXiv:2101.04577 [nucl-ex]]

Nuclear gluon shadowing factor: $R_g(x, Q^2) \approx \sqrt{\frac{\sigma^{coh}(\gamma + Pb \rightarrow J/\psi + Pb)}{\sigma^{IA}(\gamma + Pb \rightarrow J/\psi + Pb)}}$

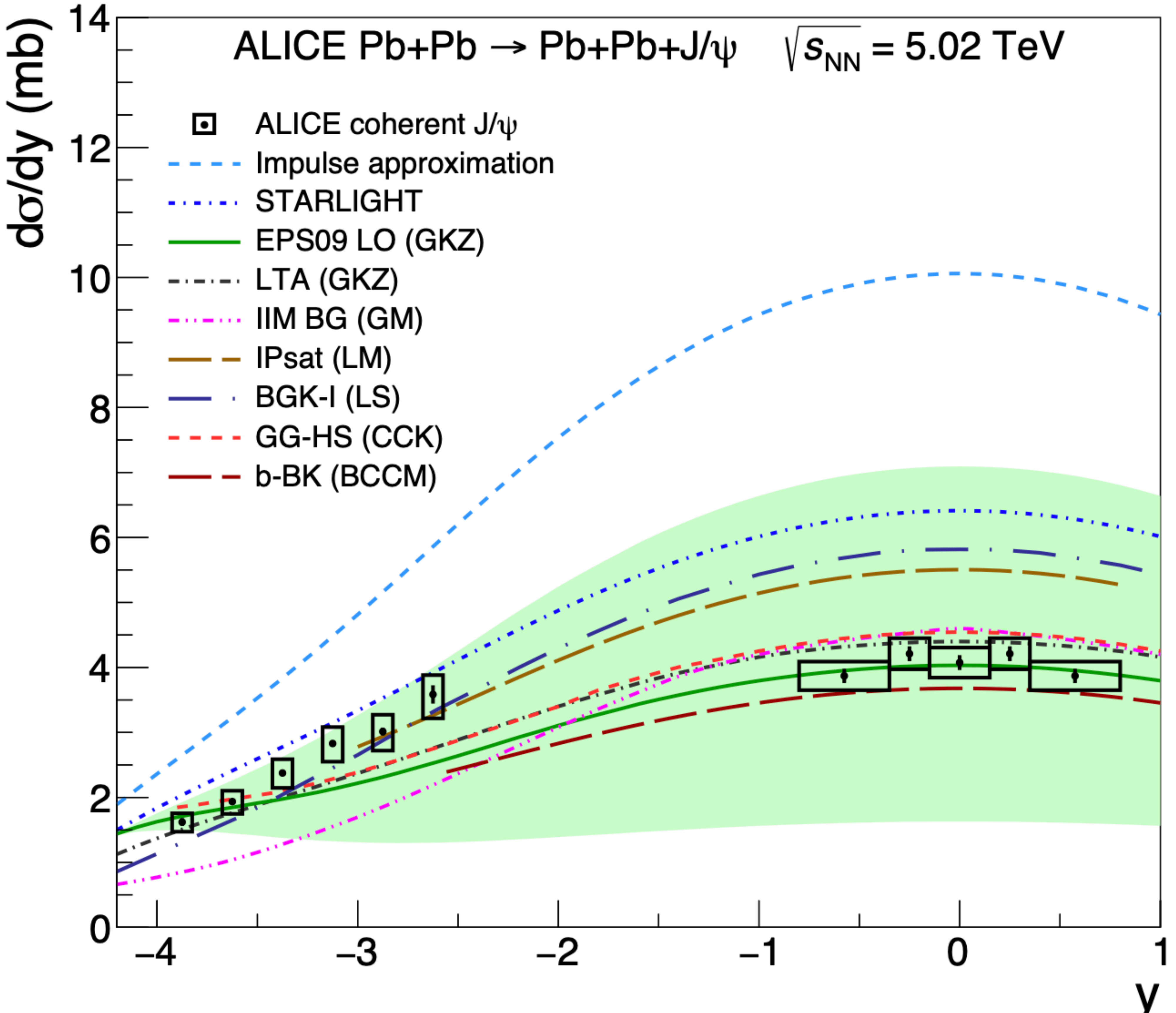
- $R_g(x \in (0.3 - 1.4) \times 10^{-3}, Q^2) \approx$ **0.65 ± 0.03 for J/ψ**

→ good agreement with $R_g(x \sim 10^{-3})$ = $0.61^{+0.05}_{-0.04}$ obtained from the measurement at $\sqrt{s_{NN}}$ = 2.76 TeV.

- $R_g(x \in (0.3 - 1.4) \times 10^{-3}, Q^2) \approx$ **0.66 ± 0.06 for ψ′**

Measurement of dσ/dy and comparison with the models

- **STARlight**: parametrisation of existing data on exclusive photoproduction of J/ψ off protons, does not include shadowing
- Indication for strong shadowing qualitatively in line with expectations from models that are based on:
  - **EPS09 LO**: parametrization of the available nuclear shadowing data
  - **LTA**: leading twist approximation of nuclear shadowing based on the combination of the Gribov-Glauber theory and the diffractive PDFs from HERA
  - **HGG-HS**: hot-spot model coupled with Gribov-Glauber theory
  - **b-BK**: color dipole approach with saturation based on solution of the impact-parameter dependent Balitsky-Kovchegov equation
- However none of the models is able to describe the full set of data
  - The data might be better explained with a model where shadowing has a smaller effect at Bjorken $x \sim 10^{-2}$ or $x \sim 5 \times 10^{-5}$.

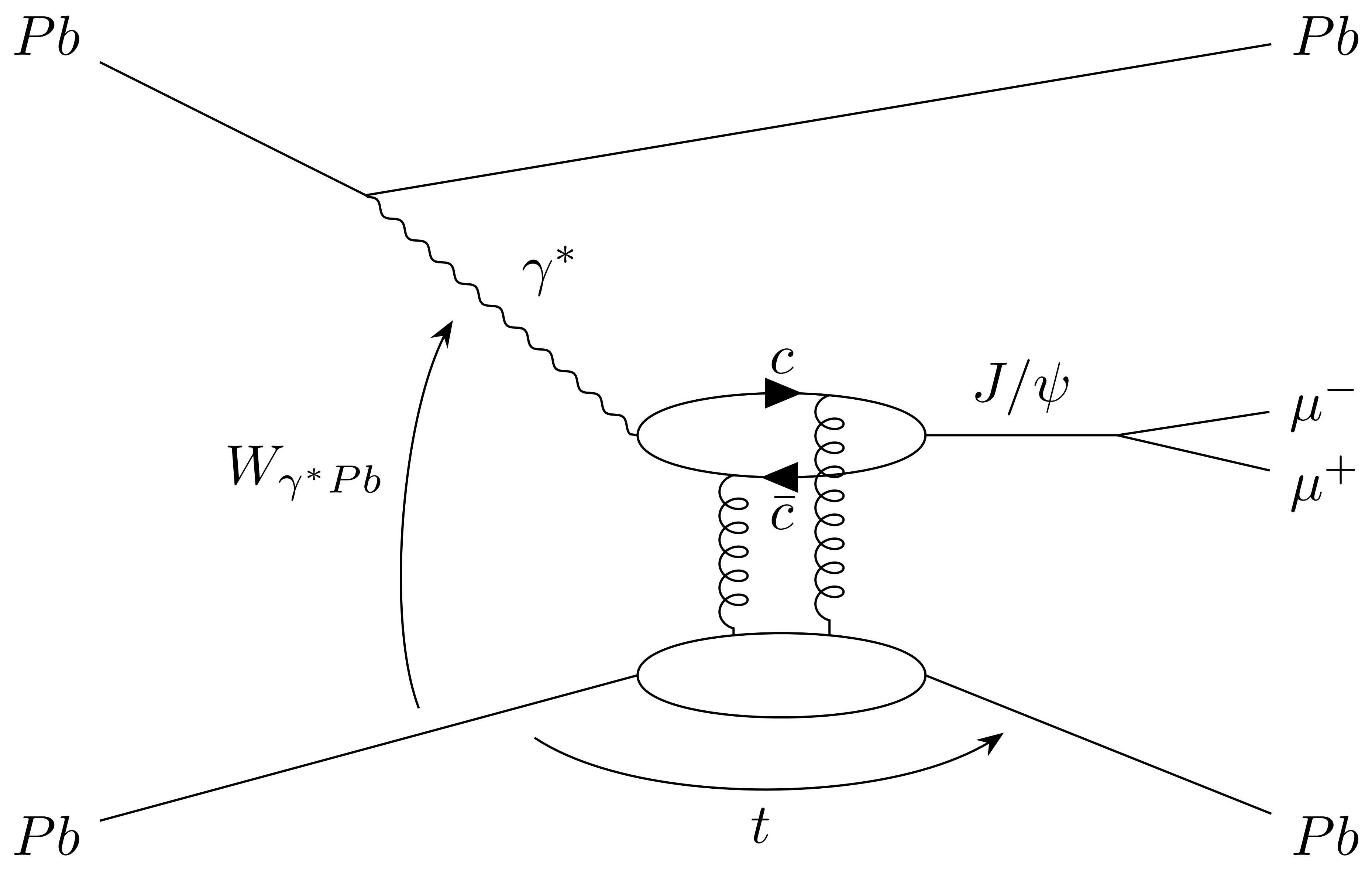


from ALICE collaboration, arXiv:2101.04577 [nucl-ex]

→ These measurements allow for a deeper insight into the Bjorken-x dependence of gluon shadowing, but do not give information on the behaviour of gluons in the impact-parameter plane.

To go further: measurement of dσ/dt (γ + Pb → J/ψ + Pb)

- First measurement of the |t|-dependence of the coherent J/ψ photoproduction cross section in Pb-Pb UPCs @ $\sqrt{s_{NN}}$ = 5.02 TeV
- $|t|^2$ is related through a two-dimensional Fourier transform to the gluon distribution in the plane transverse to the interaction
  - the study of the |t|-dependence of coherent J/ψ photoproduction provides information about the spatial distribution of gluons as a function of the impact parameter.
  - For collider kinematics $|t| \approx p_T^2$

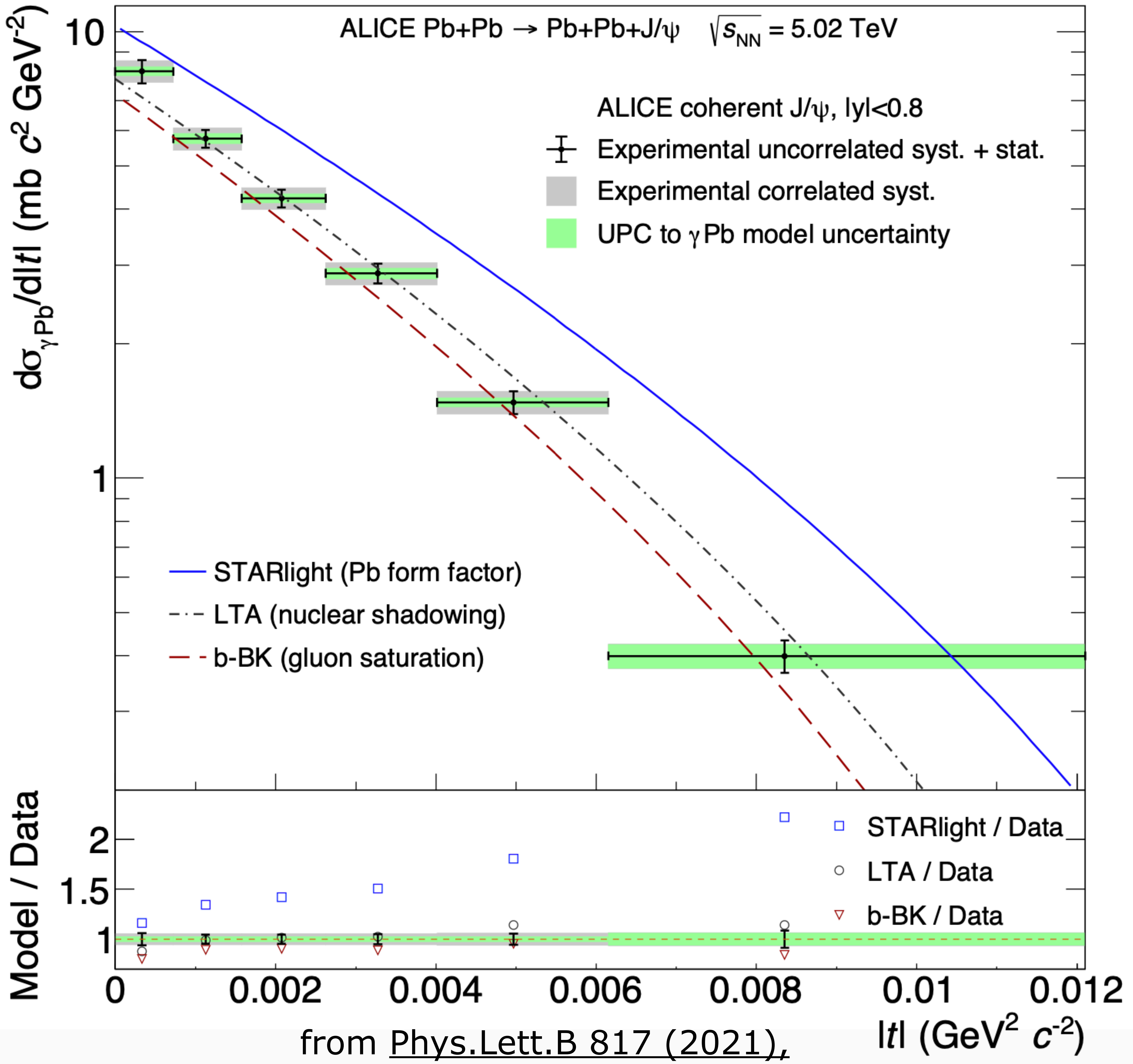


- Data sample (2018) approximately 10 times larger than that used in previous ALICE measurements at midrapidity at the lower energy of $\sqrt{s_{NN}}$ =2.76 TeV

from arXiv:2101.04623 [nucl-ex]

To go further: measurement of dσ/dt (γ + Pb → J/ψ + Pb)

- Cross sections reported for six |t| intervals
- Comparison with models:
  - **STARlight**: based on the addition of the photon and Pomeron p_T (with random phase). The Pomeron p_T distribution is given by the nuclear form factor.
  - **LTA**: leading-twist approximation (LTA) of nuclear shadowing based on the combination of the Gribov–Glauber theory and inclusive diffractive data from HERA
  - **b-BK**: based on the color dipole approach, scattering amplitude obtained from the impact-parameter dependent solution of the Balitsky–Kovchegov equation, incorporates saturation effects



from Phys.Lett.B 817 (2021), 136280

Summary

- **Measurement of $d\sigma(\gamma + p \rightarrow J/\psi + p)/dW_{\gamma^{*}p}$**
  - In Run 1: saturation has not been found
  - In Run 2: luminosity increased, increased maximum accessible energy $\sim$ 1500 GeV ($\sim$ 900 GeV in 2013), corresponding to $x \sim 8 \times 10^{-6}$ ($x \sim 3 \times 10^{-5}$ in 2013) → ongoing analysis

- **Measurement of $d\sigma(\gamma + Pb \rightarrow J/\psi + Pb)/dy$** at midrapidity $|y| < 0.8$ and in the rapidity interval $-4 < y < -2.5$ in Pb–Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV.
  - Models not able to fully describe both forward and central rapidity dependence of the measured coherent J/ψ cross section.

- **Measurement of $d\sigma(\gamma + Pb \rightarrow J/\psi + Pb)/dt$** for Bjorken-x range $(0.3 - 1.4) \times 10^{-3}$
  - Large data sample expected in the LHC Run 3 + improvement in tracking from the upgrades of the ALICE detector → should improve accuracy

Thank you for your attention!

Back up

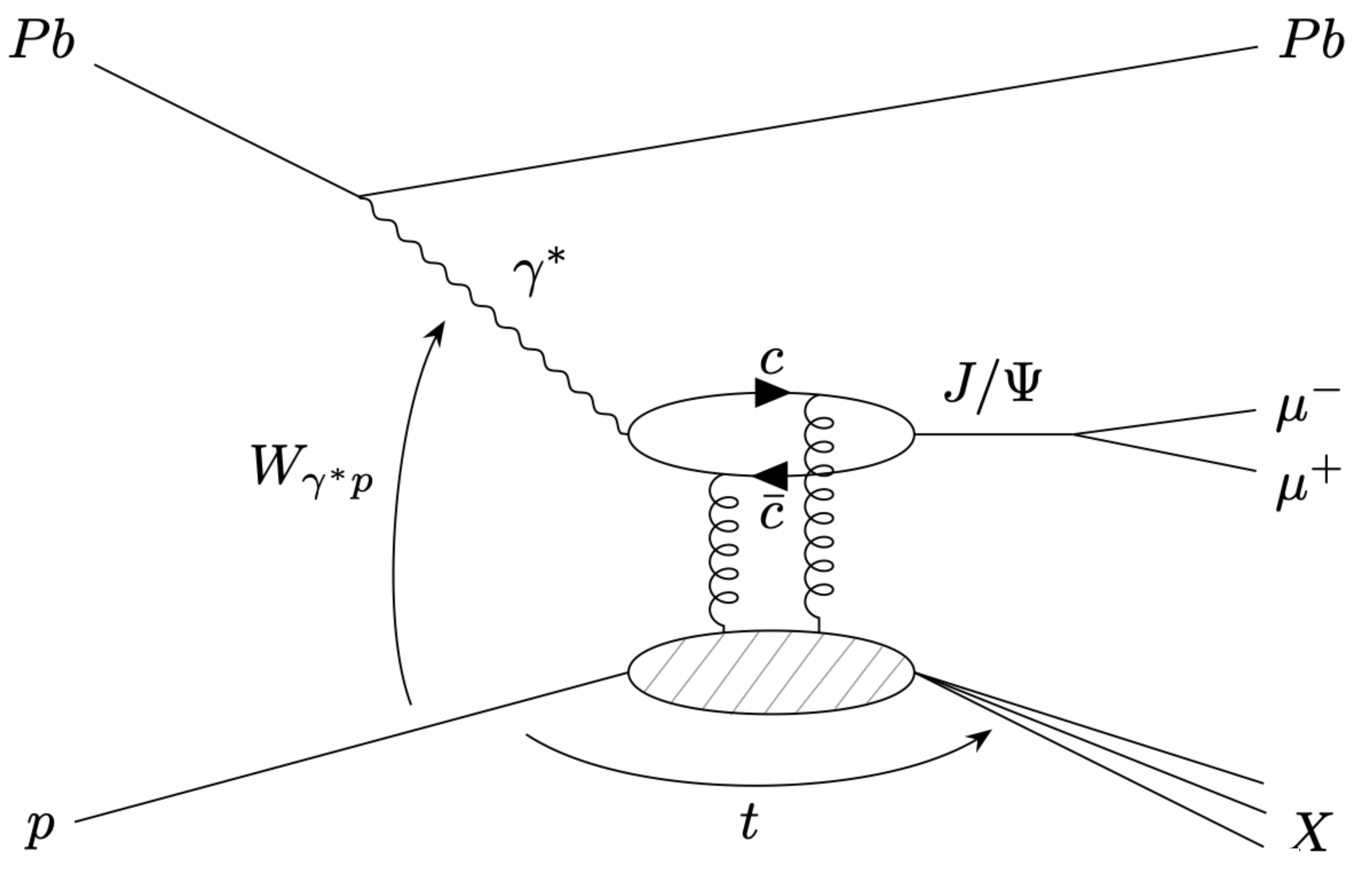
Dissociative J/ψ photoproduction

- In Good-Waker formalism (Heikki Mäntysaari 2020 Rep. Prog. Phys. 83 082201), initial and final states are required to be different

$$\frac{d\sigma^{\gamma^* p \to J/\Psi\ X}}{dt} \propto \sum_i \sum_{f \neq i} |\langle f | A | i \rangle|^2 = \sum_i \sum_f \langle i | A^* | f \rangle \langle f | A | i \rangle - \sum_i \langle i | A^* | i \rangle \langle i | A | i \rangle$$

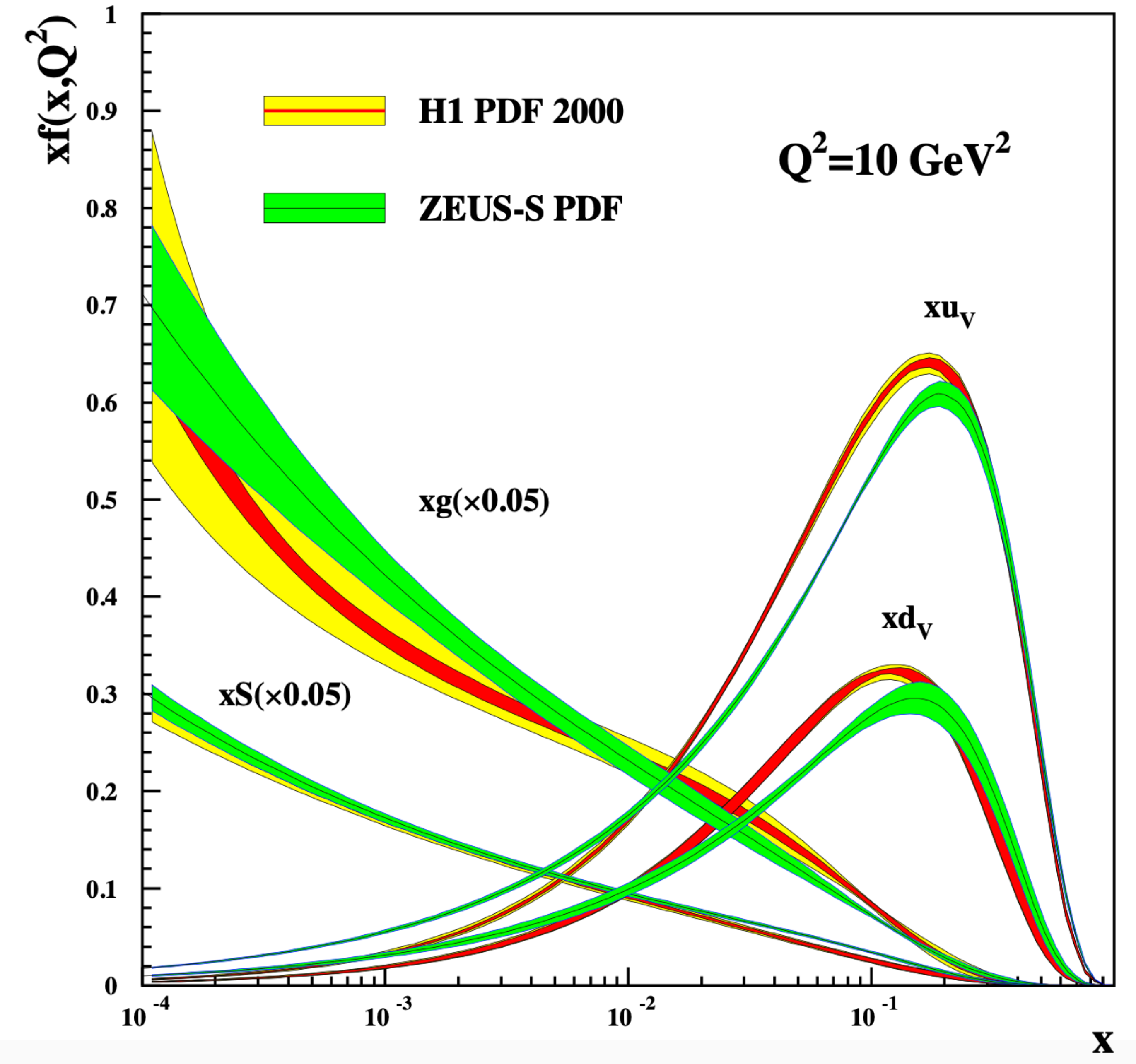
$$= \sum_i \langle i | A^* A | i \rangle - \sum_i |\langle i | A | i \rangle|^2$$

$$= \langle |A^{\gamma^* p \to J/\Psi\ p}|^2 \rangle - |\langle A^{\gamma^* p \to J/\Psi\ p} \rangle|^2$$



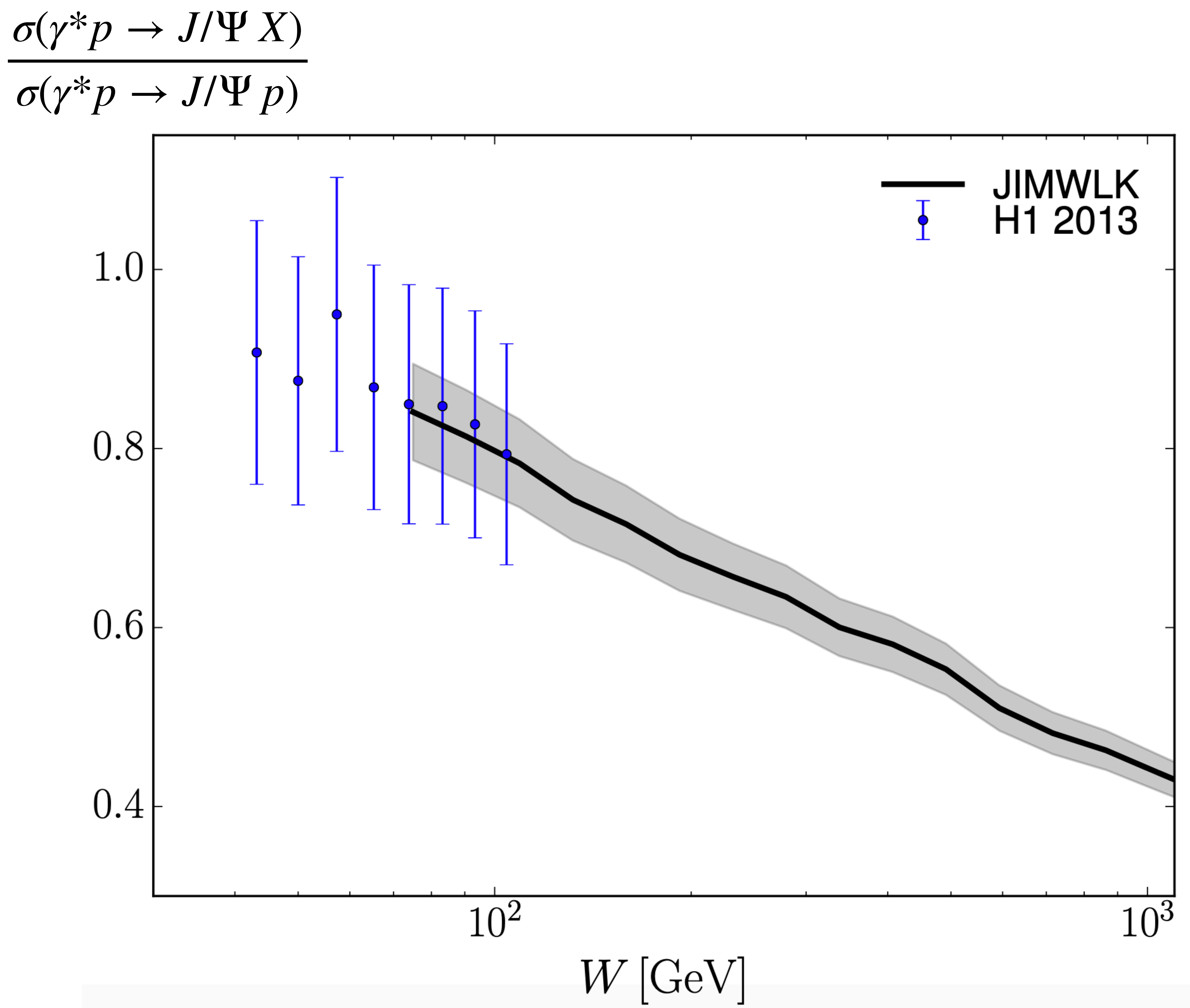
Physically: we measure the fluctuations of the configurations of the proton

- The parton density increases with decreasing momentum fraction x
  - Saturation at low x?
  - More sensitive to saturation than exclusive production, since fluctuations in asymptotic limit of high energies expected to be suppressed (black disc limit) as well as (more generically) higher t and hence smaller impact parameter and hence higher density



Saturation

- Black disk limit: area where the number of gluons stops increasing, fluctuations of the proton configurations are suppressed
- When the gluon occupation number is large enough, there are important non–linear effects. These non–linearities can manifest themselves both as
  - gluon recombination (compensates gluon radiation)
  - or as multiple interactions with an external projectile



ref: L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rept. 100 (1983) 1.

source : Heikki Mäntysaari 2020 Rep. Prog. Phys. 83 082201